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EQUATORIAL AFRICA

A CLIMATOLOGICAL STUDY

by

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13. Abstract: A climatological study of Equatorial Africa, a region that comprises Senegal, Gambia, Guinea-Bissau, Guinea, Sierra Leone, Liberia, Ivory Coast, Ghana, Togo, Benin, Nigeria, Cameroon, Equatorial Guinea, Gabon, Congo, Central African Republic, Rwanda, Burundi, Uganda, Tanzania, Kenya, Malawi, the southern parts of Mauritania, Mali, and Niger, and the northern parts of Angola, Mozambique, Zaire, and Zambia. After describing the geography and major meteorological features of the entire region, the study discusses the climatic controls of each of Equatorial Africa's eight "zones of climatic commonality" in detail. Each "season" is defined and discussed in considerable detail, to include general weather, clouds, visibility, winds, precipitation, temperature, and other hazards.

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PREFACE

This study was prepared by the United States Air Force Environmental Technical Applications Center's Readiness Support Branch (USAFETAC/DOJ) in response to a support assistance request from the Air Force Global Weather Central (AFGWC), Offutt AFB, NE. Publication of this technical note completes USAFETAC project 901033.

The project would not have been possible without the support of the many people and agencies listed here. First, our deepest gratitude to the late Walter S. Burgmann, director of the Air Weather Service Technical Library; his guidance will be missed. We also appreciate the assistance of Wayne E. McCollom, David P. Pigors, Charles Travers, Gary Swanson, Kay Marshall, Susan Keller, Susan Tarbell, Lisa Mefford, and Randa Simon of the Air Weather Service Technical Library. Without their help, much of the information in this document, obtained from sources worldwide, would not have been available to us.

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TABLE OF CONTENTS

FIGURES

Chapter 1

INTRODUCTION

Area of Interest. This study describes the geography, climatology, and meteorology of Equatorial Africa, which has been divided into the eight "zones of climatic commonality" shown in Figure 1-1 and described separately, in turn.

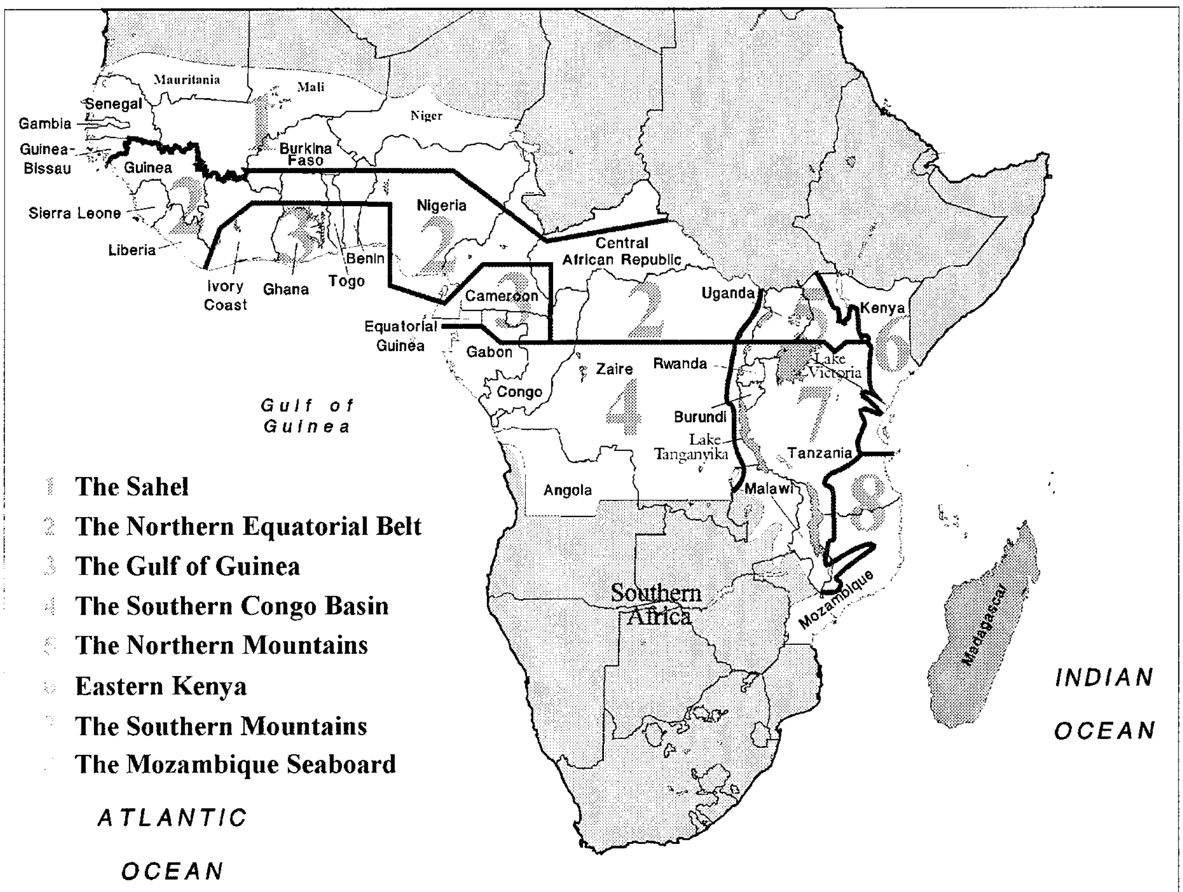


Figure 1-1. Equatorial Africa is shown here in relation to Southern Africa, a region described in USAFETAC/TN-94/005. For the purposes of this study, Equatorial Africa has been divided into the eight "zones of climatic commonality" shown: The Sahel, the Northern Equatorial Belt, The Gulf of Guinea, the Southern Congo Basin, the Northern Mountains, the Southern Mountains, Eastern Kenya, and the Mozambique Seaboard.

• ***The Sahel*** comprises Senegal, Gambia, Guinea-Bissau, the southern parts of Mauritania, Mali, and Niger, and the northern parts of Burkina Faso, Benin, Nigeria, Cameroon, and the Central African Republic. This region can be described as a semi-arid transition zone between the Sahara Desert to the north and the moister climate of the Gulf of Guinea to the south. The northern border of the Sahel is defined by the line at which annual rainfall exceeds 250 mm. The southern boundary is a line that marks the southernmost point of a wet season that runs from May to October and a dry season that runs from November to April.

• ***The Northern Equatorial Belt*** is a long and narrow west-to-east strip that comprises all of Guinea, Sierra Leone, and Liberia, as well as the northern parts of the Ivory Coast, Ghana and Togo. It also includes central Benin, southwestern Nigeria, southeastern Cameroon, northern Congo, northwestern Zaire, and the southern part of the Central African Republic. The wet season in this zone is from April through October, with a dry season from November through March.

• ***The Gulf Of Guinea*** is an irregularly shaped coastal climatic zone whose boundaries are drawn strictly by the limits of its wet and dry seasons. The western part of the zone includes the southern portions of the Ivory Coast, Ghana, Togo, and Benin, along with the southwestern corner of Nigeria. The eastern part of the zone, after skipping over the gulf coasts of Nigeria and Cameroon (a southward extension of the Northern Equatorial Belt, in which there is no dry season), comprises Equatorial Guinea, southern Cameroon, northern Gabon, and a small portion of northwestern Congo. There are two separate and distinct wet and dry seasons in this zone: the wet seasons run from March to June and from September to October; the dry seasons run from November to February and from July to August.

• ***The Southern Congo Basin*** comprises the southern parts of Gabon and Congo, the northern part of Angola, and southeastern Zaire. The northern boundary is marked by the equator, while the southern boundary is a line that marks the limit of the rivers that feed into the Congo Basin. The entire zone is very wet, with a wet season that lasts from October through April. There is a very short June-August dry season.

• ***The Northern Mountains*** is a zone that comprises northern Uganda, northwestern Kenya, and a small part of northeastern Zaire. The western and eastern boundaries are formed by the 900-meter contours. The southern boundary (which runs generally along the equator) marks the southern limit of the April-November wet season and the December-March dry season.

• ***The Southern Mountains*** includes southern Uganda, southwestern Kenya, most of Tanzania and Malawi, portions of Mozambique, western Zambia and Zaire, and all of Rwanda and Burundi. Boundaries are marked by the 1,500-meter contour everywhere except in the north (where reversal of the seasons at the equator defines the northernmost limits of the zone) and in the east, where it is marked by the 900-meter contour. There is a November-April wet season and a May-October dry season.

• ***Eastern Kenya*** is a relatively small climatic zone made up of eastern Kenya and northeastern Tanzania. The western boundary is the 900-meter contour, while the southern boundary is defined by the dual wet and dry seasons. The two dry seasons run from January to February and from June to September. The two wet seasons run from March to May and from October to December.

• ***The Mozambique Seaboard*** includes the southern portion of Tanzania and most of northern Mozambique. The western boundary is the 1,000-meter contour, except where the Zambezi River valley allows Indian Ocean moisture to be advected farther inland. The southern boundary is the southernmost limit of the Indian Ocean Monsoon Trough and the northernmost limit of the trade winds (20° south). The northern boundary is marked by the limits of the December-April wet season and the May-November dry season.

Study Content. Chapter 2 provides a general discussion of the major meteorological features that affect Equatorial Africa. These features include semipermanent climatic controls, synoptic disturbances, and mesoscale and local features. The individual treatments of each region in subsequent chapters do not repeat descriptions of these phenomena; instead, they discuss specific effects of these features unique to that region. Therefore, meteorologists using this study should read and consider the general discussion in chapter 2 before trying to understand or apply the individual climatic zone discussions in chapters 3 through 10. This is particularly important because the study was designed with two purposes in mind: first, as a

master reference for Equatorial Africa; and second, as a modular reference to each individual region. Chapters 3 through 10 amplify the general discussions in Chapter 2 by describing the geography, climate, and meteorology of the eight "zones of climatic commonality" shown in Figure 1-1. These chapters provide detailed discussions of these eight zones, each of which is known to feature reasonably homogeneous climatology and meteorology. In mountainous areas, however, weather and climate are not necessarily internally homogeneous; they can be distinctly different from areas immediately adjacent.

In each region, geography is discussed first (including topography, rivers and drainage systems, lakes and water bodies, and vegetation). Next, major climatic controls, and, if appropriate, special climatic features are described. Weather for each season is then discussed, organized in the following order:

- General Weather
- Sky Cover
- Visibility
- Winds (including upper winds)
- Precipitation
- Thunderstorms
- Temperature
- Other Hazards

All eight climatic zones of Equatorial Africa have wet and dry seasons instead of the standard temperate-zone seasons (winter, spring, summer, and fall). Transitions between wet and dry seasons are, in most cases, too short to warrant separate transition season discussions. The length of each season varies from region to region.

Conventions. The spellings of place names and geographical features are those used by the United States Defense Mapping Agency's Aerospace Center (DMAAC). Distances and elevations are in meters below 10 kilometers and in kilometers above. Cloud and ceiling heights are in feet. When the term "ceiling" is used, it means 5/8 cloud coverage or greater *at any level* unless specified otherwise. Temperatures are in degrees Celsius (° C). Wind speeds are in knots. Precipitation amounts are in millimeters (mm). Most synoptic charts are labeled in Greenwich Mean Time (GMT or Z). When synoptic charts are not provided, only local time (L) is used.

Unless otherwise stated, cloud bases are above ground level; tops are above mean sea level. Since cloud bases are generalized over large areas, readers must consider terrain in discussions of cloud bases in and around the mountains.

In the figures that give mean monthly rain and thunderstorm days, "rain days" include those on which WMO present weather codes 20, 21, 25, 27, 50 through 65, 80 through 82, 91 and 92 are reported. "Thunderstorm days" are those on which codes 17, 29, and 91 through 99 are reported.

Data Sources. Most of the information used in preparing this study came from two sources, both within USAFETAC. Studies, books, atlases, and so on were supplied by the Air Weather Service Technical Library (AWSTL or USAFETAC/DOL). Climatological data came directly from the Air Weather Service Climatic Database, through OL/A, USAFETAC—the branch of USAFETAC responsible for maintaining and managing this database.

Related References. This study, while more than ordinarily comprehensive, is certainly not the only source of climatological information for the military meteorologist concerned with Equatorial Africa. USAFETAC/DS-87/034, *Station Climatic Summaries—Africa,* provides summarized meteorological observational data for several major airports in the study area. Staff weather officers and forecasters are urged to contact the AWS Technical Library for more information.

Chapter 2

MAJOR METEOROLOGICAL FEATURES OF EQUATORIAL AFRICA

Sea-Surface Conditions. Ocean currents play a major role in determining the continent's weather. Warm waters *destabilize* the boundary layer, generally resulting in cumuliform clouds, while cold waters *stabilize* the boundary layer, generally producing *stratiform* clouds. Figure 2-1 shows the currents near the study area, while Figure 2-2 shows mean sea-surface temperatures for January, April, July, and October. Technically, the cold Canary Current (not shown) does not reach the region, but its effects can be seen in the lower temperatures off the northwest coast in Figure 2-2 for January and April. The colder waters move farther north in July and October.

The Equatorial Countercurrent and the Guinea Current bring warm waters into the Gulf of Guinea all the way to Cameroon. The Guinea Current begins at roughly 14° W. The Equatorial Countercurrent is weaker when the Canary Current affects the region.

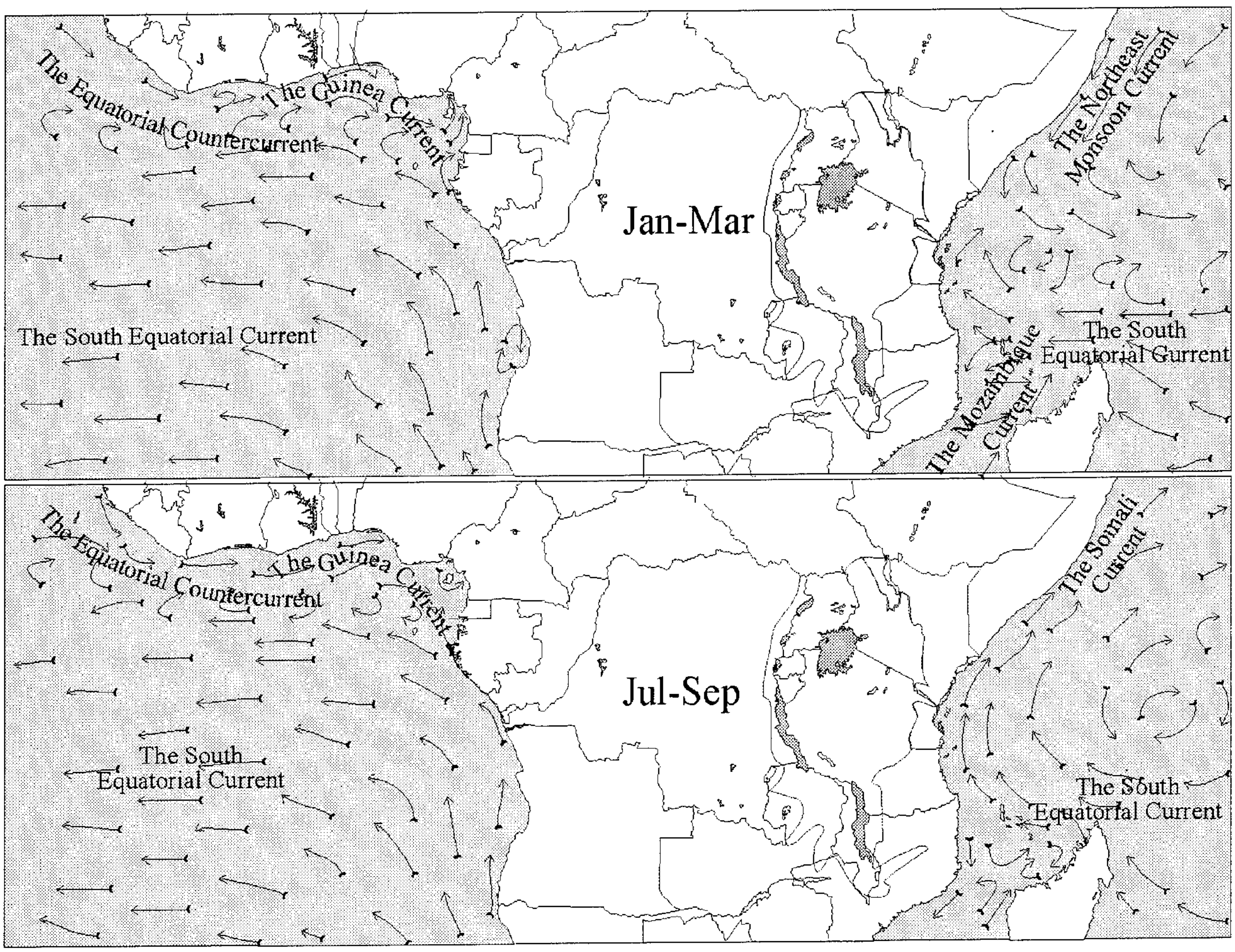


Figure 2-1. Ocean Currents and Prevailing Directions. Currents Indicated by Arrows. Currents around Madagascar vary with windflow.

The Northeast Monsoon Current is present from December to April. The Somali Current is present from May to November, its southwesterly flow produced by the Southwest Monsoon; it is stronger than the Northeast Monsoon Current.

Madagascar causes the warm South Equatorial Current in the Indian Ocean to split; one branch flows north of the island and down the east coast, while the other becomes the warm Mozambique Current that flows down the west side of the Mozambique Channel. A number of eddies form in the eastern sections of the channel, making the flow complex. At about 25° S, the Mozambique Current becomes the Agulhas Current, which takes warmer waters south until they converge with the West Wind Drift, which is southwest of the continent and not shown.

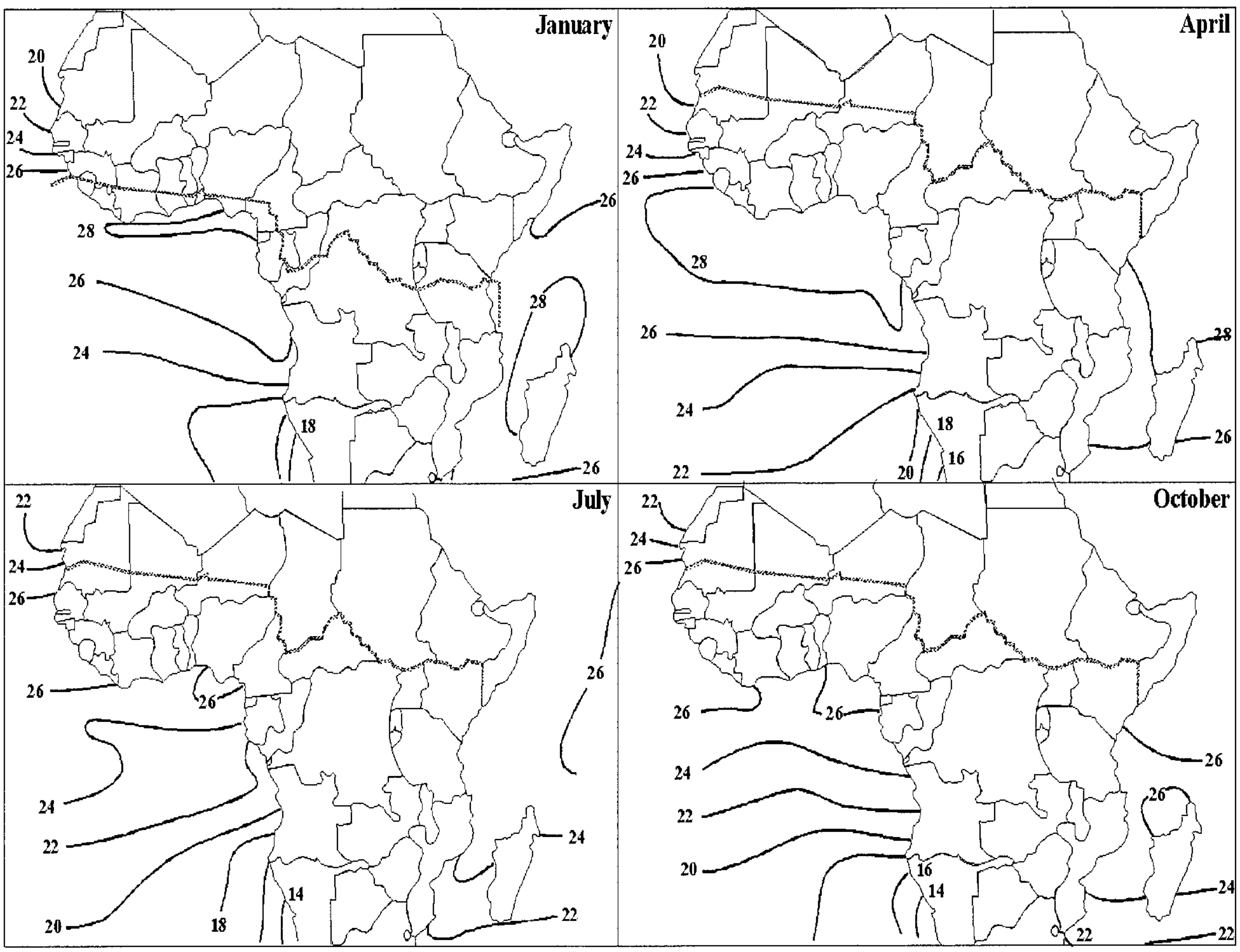


Figure 2-2. Mean January, April, July, and October Sea-Surface Temperatures (° C).

Maritime Atmospheric Pressure Features

The Southern Oscillation (El Niño, La Niña). The term "Southern Oscillation" originally referred to a sequence in which high and low atmospheric pressure systems alternated over the tropical waters of the Indian and Pacific Oceans. The Southern Oscillation is now known to be a complex, global atmospheric and oceanic phenomenon. Although not yet fully understood, it appears to be connected to changes in the monsoon over India and the Indian Ocean and the sea-surface temperatures in the Atlantic and Indian Oceans.

The Southern Oscillation is in two phases: a warm El Niño and a cold La Niña, with short transitions between the two. The time needed to complete a cycle is irregular; it varies between 2 and 10 years, with an average of three. The El Niño phase has an average length of 18 months. El Niño begins around Christmastime in the eastern Pacific (hence the name, which means "The Child"). In Equatorial Africa, the El Niño's influence peaks 12 months later, during the following southern-hemisphere summer (December-March).

Figure 2-3 shows the areas directly or indirectly affected by the Southern Oscillation. In the area enclosed by the solid line, precipitation from November to May is generally less than normal during an El Niño, and greater than normal during a La Niña. The smaller area enclosed by the dashed line gets more precipitation when an "El Niño-like" event occurs in the Atlantic and raises SSTs; although these events have an interannual variability, they are on a different cycle, with peaks 5-6 years apart.

All the areas in Figure 2-3 see changes in weather based on changes to the Near Equatorial Trough (NET) during southern hemisphere summer. Note that the shaded and solid-line areas experience opposite effects since the NET is either farther north (La Niña) or south (El Niño) than normal. In the dashed-line area, there is more precipitation when Atlantic sea-surface temperatures are higher (as in an El Niño), but the cycle appears to be independent of the Southern Oscillation; for example, the area saw a precipitation maximum in 1984, a year after the end of the 1982-83 El Niño. There are some indications that an El Niño may cause drier conditions in the Sahel, but more research is needed to confirm these and other possible affects.

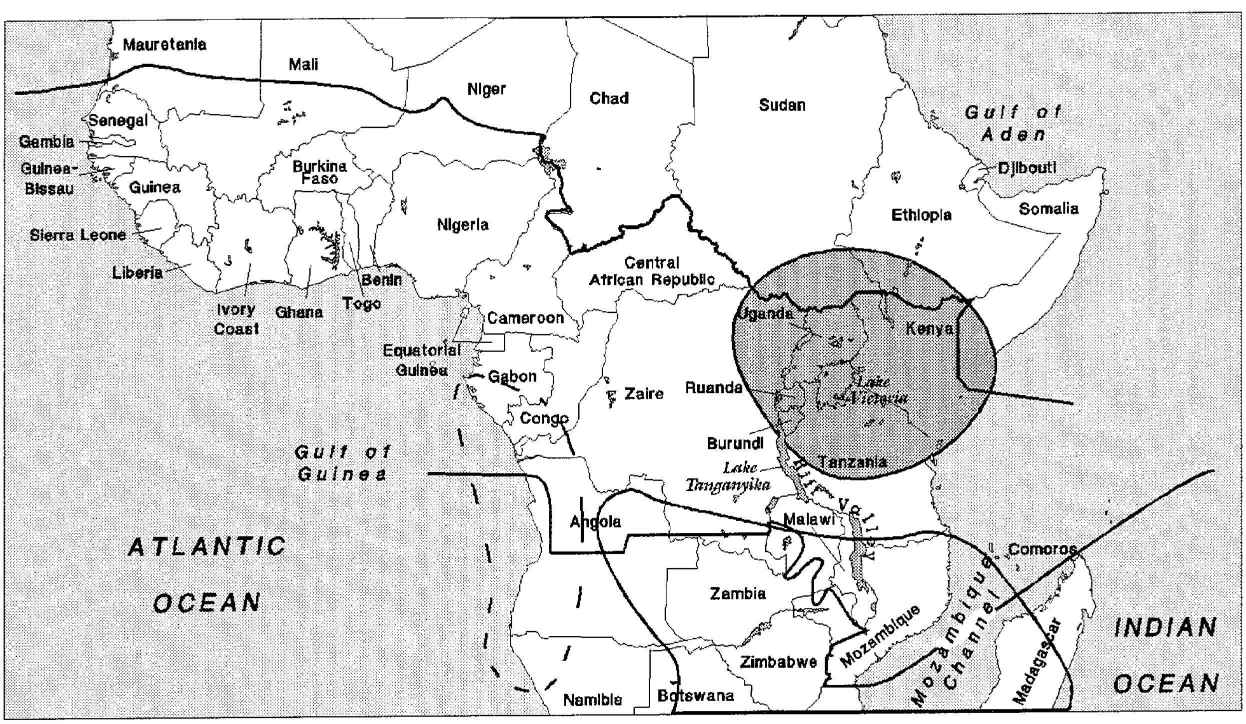


Figure 2-3. Regions Affected by the Southern Oscillation.

The Azores High. Figures 2-4a & b (on pages 2-6 and 2-7) show the Azores High's mean positions and sea-level pressures for January, April, July, and October. Mean pressures and positions vary from 1021 mb at 29° N, 29° W in January to 1025 mb at 37° N, 37° W in July. The high ridges into Morocco and Mauritania in northern hemisphere winter, blocking frontal systems from moving into West Africa off the Atlantic. Outflows from the Azores and South Atlantic Highs converge to form the Near Equatorial Trough (NET); specifically, a monsoon trough. Flow from the Azores High becomes very hot, dry, and dust-laden as it crosses the desert. It is then forced up over South Atlantic air.

The South Atlantic (St Helena) High. Figures 2-4a & b show the high's mean positions and sea-level pressures for January, April, July, and October. Mean pressures range from 1018 mb in March to 1025 mb in September. The cell migrates northwestward from 32° S, 8° W in January to 26° S, 12° W in July. Surface wind speeds average 13 knots to the north of the high and 25 knots to the south along the mid-latitude storm track.

The high slopes equatorward with height. Because of differential heating of the continents and oceans (which is strongest in the southern hemisphere during January), the South Atlantic High is stronger and farther north in winter than in summer, the opposite of its northern hemisphere counterpart.

Flow from the South Atlantic High plays a major role in determining the weather across much of the study area. For example, it causes convection in south-central Africa where the flow meets South Indian Ocean flow, forming the Congo Air Boundary. The eastern limb of the cell remains relatively fixed along the southwest coast, where there is strong subsidence and a low-level inversion. Maximum coastal subsidence, at roughly 25° S, prevents most frontal systems from penetrating northward along the southwest coast. Flow around the eastern end of the high produces the cold Benguela Current, which further stabilizes the coastal area.

The South Indian Ocean (Mascarene) High. Figures 2-4a & b show this high's mean positions and sea-level pressures for January, April, July, and October. Mean pressure ranges from 1021 mb in April to 1028 mb in August; pressure can exceed 1040 mb in winter. Movement is mainly east-west from 30° S, 87° E in January to 29° S, 65° E in July. Like the South Atlantic High, it is stronger and farthest north in the winter. The high slopes equatorward and westward with height.

The South Indian Ocean high's large east-west movement results in a seasonal variation of increased stability and more frequent inversions in the southern hemisphere winter over Madagascar and southeast Africa. Since the high is closer to the coast, it produces a trade-wind inversion that is lower in the southern-hemisphere winter. The depth of the southeasterly trade winds off the coast varies from 2,000 to 4,000 meters.

In central Africa, the flow from the South Indian Ocean High meets South Atlantic High flow to produce the Congo Air Boundary. The South Indian Ocean high is the main steering mechanism for tropical cyclones affecting Madagascar and southeast Africa.

Continental Atmospheric Pressure Features

The Saharan High is a mean large-scale, high-pressure area in the eastern Sahara. It develops in October or November and dissipates by May. The Saharan High, part of the subtropical belt of high pressure, has dynamic origins. Strong radiative cooling enhances its surface strength. Its day-to-day position and strength vary as deep polar troughs enter northern Africa, particularly between January and early April. The Saharan High generally moves eastward ahead of disturbances, or disappears entirely off the synoptic chart. It usually reforms at the surface within 12-24 hours after a frontal passage.

Figures 2-4a & b show January, April, and October positions and mean sea-level pressures of the

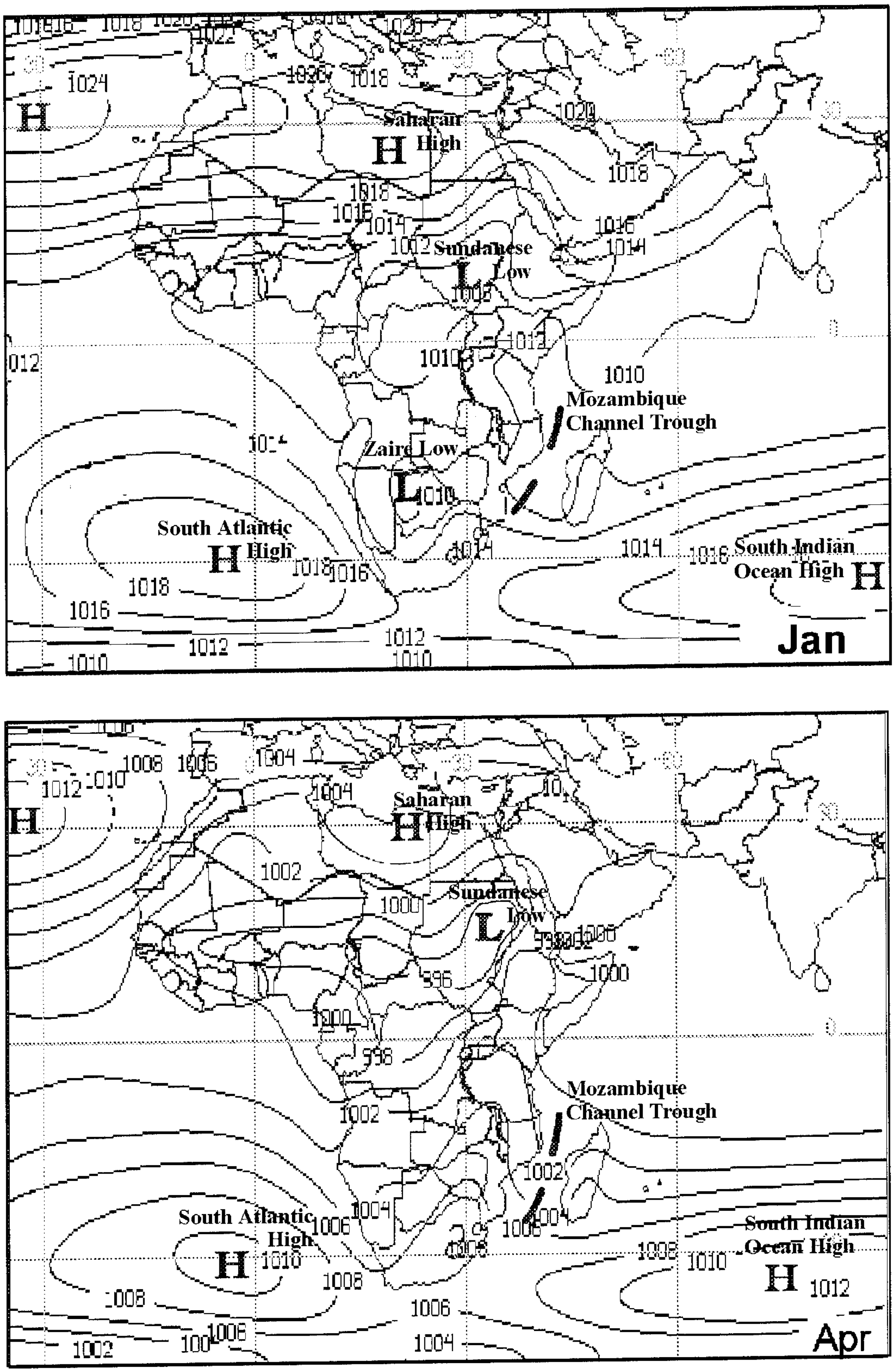


Figure 2-4a. Mean January and April Positions of Major Pressure Systems Affecting Equatorial Africa.

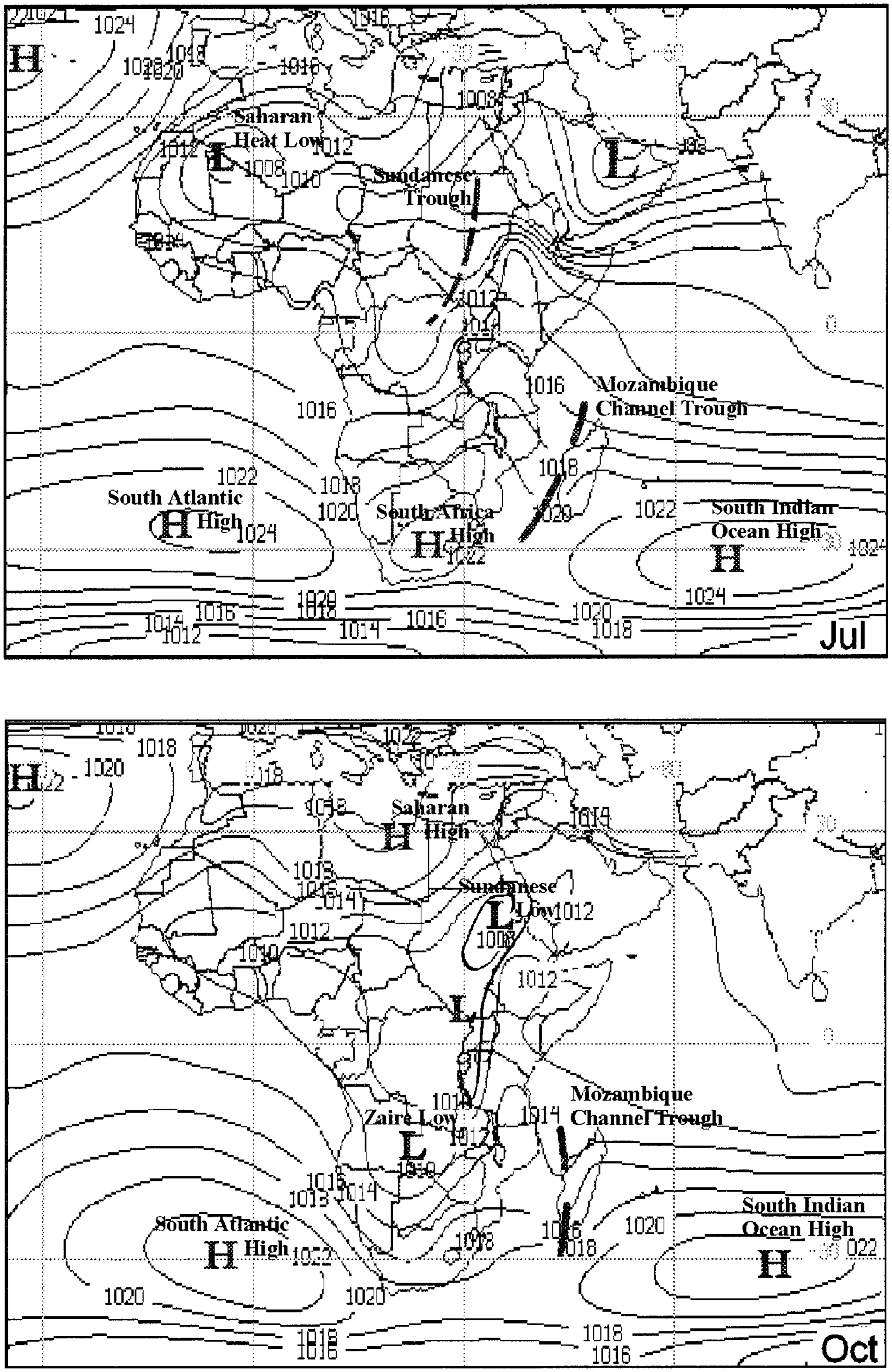


Figure 2-4b. Mean July and October Positions of Major Pressure Systems Affecting Equatorial Africa.

Saharan High; it is not present in July. The Azores and Saharan Highs often produce an extensive high-pressure ridge over northern Africa. In April, the Saharan High's mean position shifts slightly eastward to 22° E due to increased daytime heating and the increase in Atlas Low activity. By the time the outflow from the Saharan High crosses the Sahara, it has become hot, dry, and dust-laden. The northeast winds produced are referred to as the "Harmattan," and the dust-laden air as "Harmattan haze."

The Zaire/Zambian Low is primarily a thermal low that forms along the Congo Air Boundary where outflow from the South Atlantic and South Indian Ocean Highs meet; it moves north-south with this convergence zone. Present year-round, it shows on the mean pressure charts only during southern hemisphere spring and summer (see Figures 2-4a and b, January and October). It averages 1006 mb in January over the Upper Veldt to the northwest of Lake Kariba. During April, it shifts northward into south-central Zaire and weakens. By May, it has become just a weak, broad area of low pressure. It moves back to the south and intensifies from August to October.

The Sudanese Heat Low. Varying from 1004 to 1012 mb, this low often marks the eastern edge of large-scale, equatorial African low pressure in the northern hemisphere. The Sudanese Low lies over the high plateaus of southeastern Sudan and southwestern Ethiopia between December and March, as shown in Figure 2-4a. It migrates northward to 15-20° N in April and May. Between June and September, it becomes the broad, poorly defined low-pressure area shown in Figure 2-4b for July; in October, it reappears as a closed low.

The Saharan Heat Low begins to develop over the Sahara near 25° N, 3° E, in late March or early April and lasts until mid-October. By July, it has a mean surface pressure of 1004 mb (Figure 2-4b). It is sustained by intense solar radiation through the summer, and can extend up to 750 mb. The Saharan Heat Low anchors the western end of the large-scale low-pressure trough extending from Pakistan westward to the Sahara. This persistent circulation introduces large amounts of dust into the atmosphere. It also assists in Atlas Low development.

Monsoon Climate. The term "monsoon" (from the Arabic *mawsim*, "seasons") is commonly applied to those areas of the world in which there is a seasonal reversal of prevailing winds, but the generally accepted definition of a monsoon climate includes satisfaction of all four of the following criteria (after Ramage, 1971); Figure 2-5 shows the extent of the "monsoon climate" across Africa, according to Ramage's criteria.

- Prevailing seasonal wind direction changes by at least 120 degrees between summer and winter.

- Summer and winter mean wind speeds both equal or exceed 10 knots (5 meters/sec).

- Wind directions and speeds must remain steady.

- No more than one system consisting of a low and a high may occur during January or July in any 2-year period within a 5-degree square surrounding the area.

The Near Equatorial Trough (NET), variously called the "Intertropical Convergence Zone" (ITCZ), the "Intertropical Discontinuity (ITD)," and the "Meteorological Equator," is caused by the converging outflows of the northern and southern hemispheres' subtropical highs. Convection can be frequent, but there is rarely a continuous line along the NET axis. Two specific forms of the NET are *trade-wind troughs* (or *trade-wind convergence zones*) and *monsoon troughs.*

Trade-wind troughs form from the confluence of northeasterly and southeasterly trade-wind flow. Most associated cloudiness occurs along the axis of confluence. *Monsoon troughs* are characterized by a directional shear zone, with westerlies on the equatorward side and easterlies on the poleward side. Most associated cloudiness occurs equatorward of the trough. Specific examples of both troughs are discussed below.

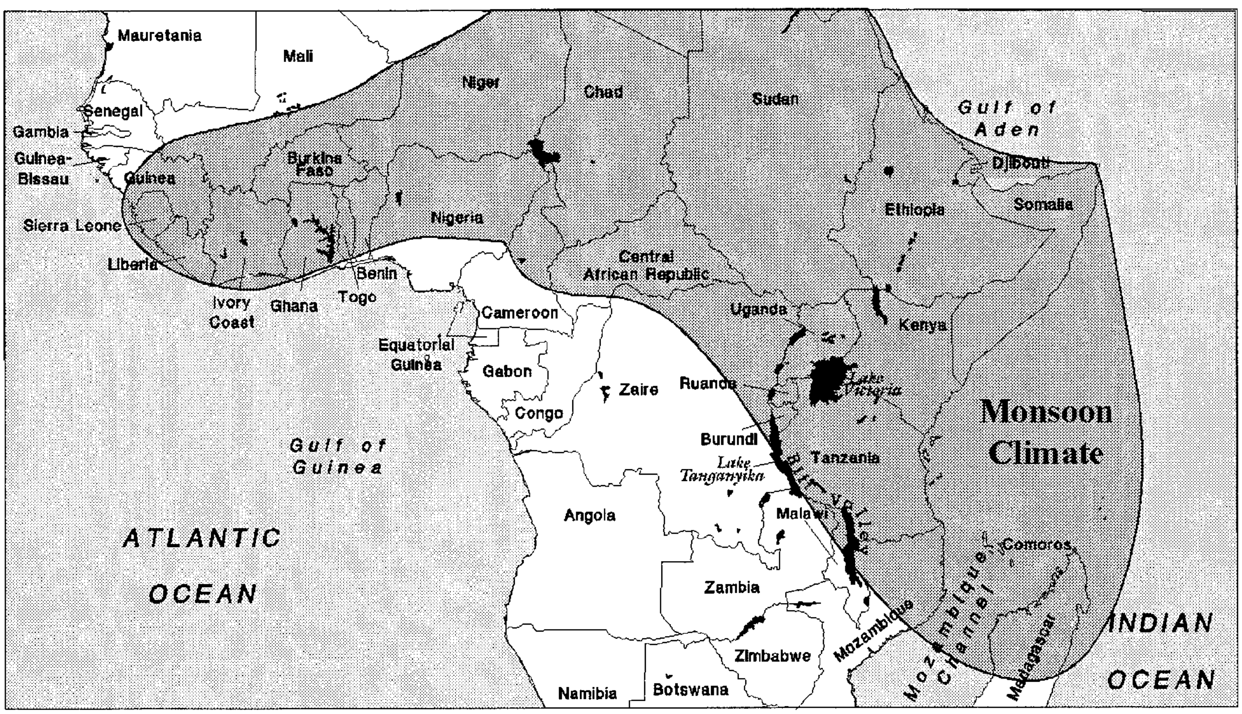


Figure 2-5. Extent of the Monsoon Climate (shaded area) Across Equatorial Africa (from Ramage, 1971).

A *trade-wind trough* forms over the Atlantic, with convection occurring near the trough axis. The Atlantic's moderating influence keeps the trough in a fairly narrow latitude band. In the spring, coastal waters are cooler than the Sahara, delaying the northward movement near the west coast and shortening the wet season in and around Senegal. South Atlantic coastal waters are cool year-round, preventing the trough from moving into the southern hemisphere, except for El Niño-like events.

A *monsoon trough* produced by convergence of outflows from the Azores and South Atlantic Highs forms west of the Great Rift Valley year-round. Dry, subtropical Saharan air lies to the north, with moist equatorial Atlantic air to the south. The boundary between these air masses is also referred to locally as the "Intertropical Discontinuity (ITD)." The trough slopes to the south with height; convection develops well south of the surface trough. This monsoon trough follows the sun's annual movement, trailing it by about 6 weeks. The trough's northward movement is more gradual than its southward movement. It is farthest north in July and August. From March to May, trough movements are characterized by brief northward surges (1-3 days) when deep Atlas Lows temporarily replace or weaken the Azores/Saharan High pressure ridge over the Sahara. The trough moves northward in response to the lower pressure and is driven southward when high pressure builds behind the front. Northward shifts are usually about 90 km, but the NET has moved 12 degrees of latitude in 24 hours. These highs are still strong in March, but they are much weaker and less frequent in April and May, allowing the surface monsoon trough to move northward gradually. Between December and July, the South Atlantic High also strengthens and moves from 32° S to 26° S, driving the trough northward. Mean surface winds back through north and west at individual stations as the monsoon trough approaches and moves north. The move southward is faster as the Saharan High develops and the South Atlantic High weakens and moves south.

From December to February, a trade-wind trough forms over East Africa, with a monsoon trough over Madagascar and the South Indian Ocean. These features are produced by convergence of the Northeast Monsoon and the South Indian Ocean High. The monsoon trough over the South Indian Ocean is a source of tropical cyclones.

From June to September, a secondary trough can develop in a buffer zone near the equator, where the winds switch from southeasterly to southwesterly. This cloud band (referred to as the "Southern Equatorial Trough," or SET) is normally in the central Indian Ocean. Organized convective disturbances in the SET move west and occasionally reach East Africa.

Fronts passing to the south affect the NET during the southern-hemisphere summer (December to February). Convection increases with an approaching front but is reduced afterward when high pressure moves into or ridges into the southern African interior. The NET can move southward 5 degrees of latitude with the approaching system; it can then be driven northward by the high pressure behind it. Strong cold fronts that penetrate as far north as Zambia dissipate the convection until the front moves off the sub-continent. Conditions over Equatorial Africa temporarily become as dry as in the winter.

Figures 2-6a through 2-6l show each NET monthly position (dashed line), with the zone of associated convection it produces (solid line), along with representative satellite photos. The associated convection zones average two organized convective systems at least 200 km long per each 1-degree grid square. These "cloud clusters" (individual cells embedded in a common cirrostratus canopy) are responsible for most of the rainfall received. This criterion is also in agreement with available satellite cloud composites. The number of occurrences increases toward the center of each area. Monthly and yearly variability is greatest on the edges. The satellite photos are NOAA Mercator projections of polar orbiter data.

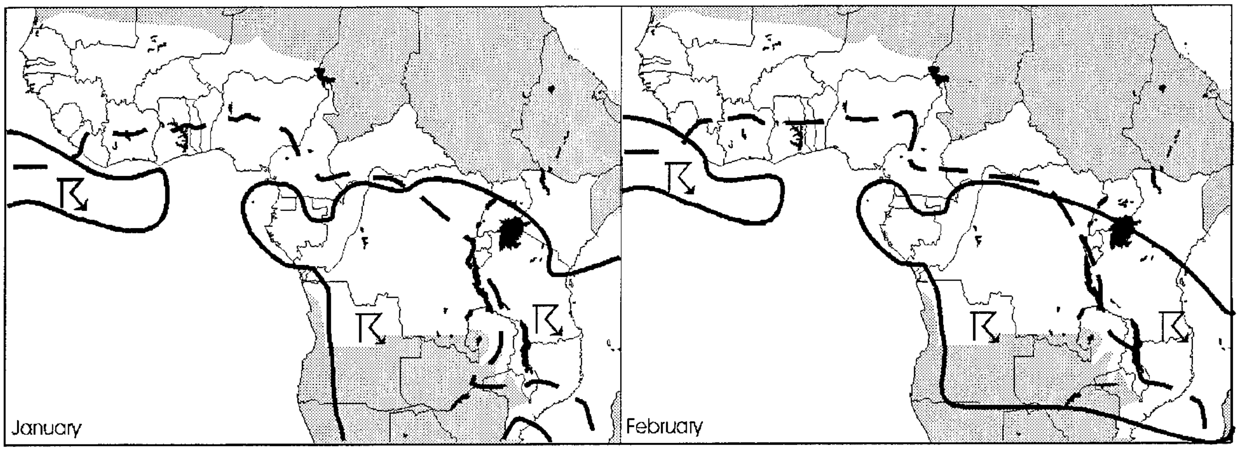


Figure 2-6a. Mean January and February Positions of NET (dashed) and Associated Convection (solid). Convection is at its maximum near Lake Tanganyika. In February, it moves northward.

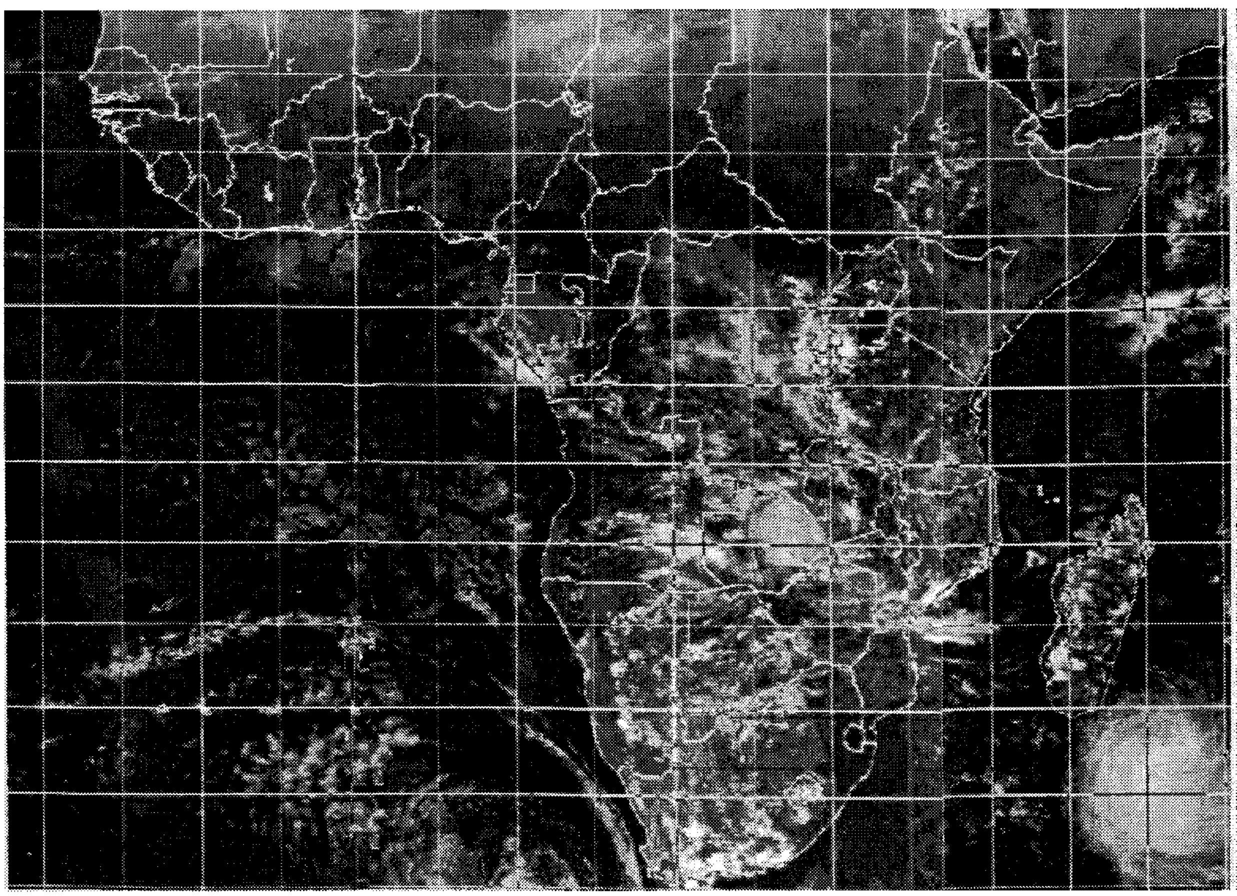


Figure 2-6b. NOAA Visual Image, 31 January 1989. Most convection is in the southern hemisphere except for the Gulf Guinea. Tropical cyclones affect Madagascar (NOAA NESDIS).

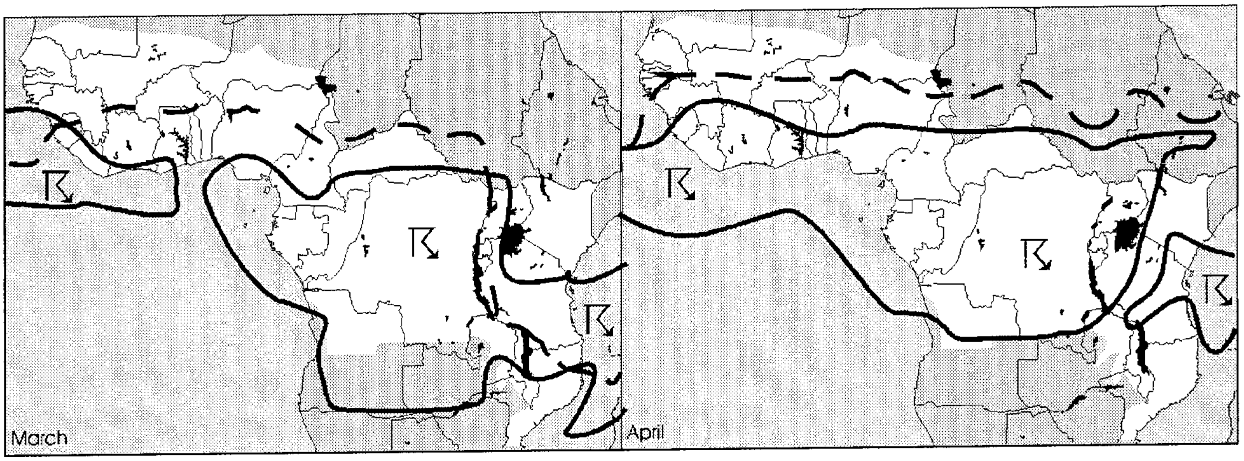


Figure 2-6c. Mean March and April Positions of NET (dashed) and Associated Convection (solid). Convection is at a maximum near Lake Tanganyika.

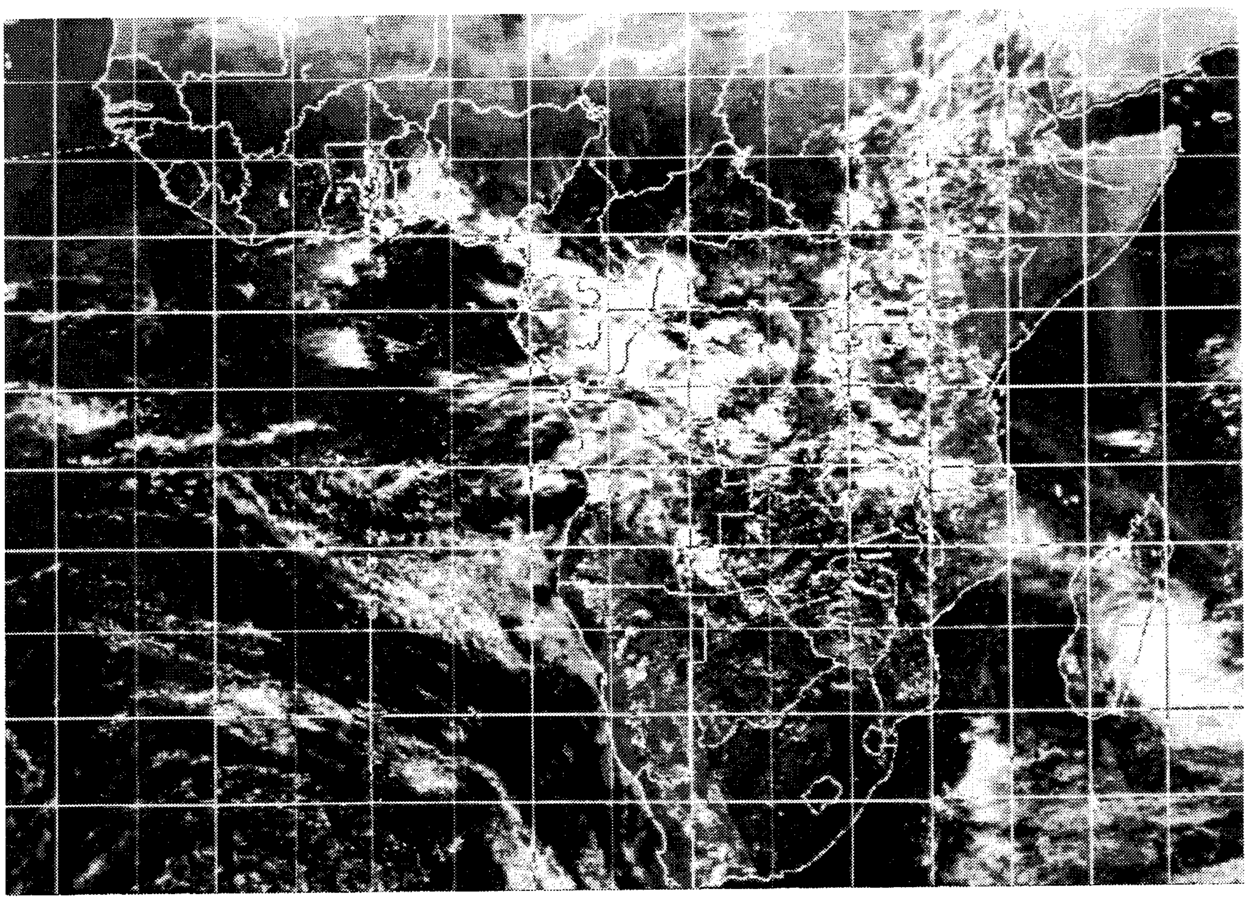


Figure 2-6d. NOAA Visual Image, 28 March 1989. Convection has started to shift northward, especially along the Gulf of Guinea coast. Tropical cyclones affect Madagascar (NOAA NESDIS).

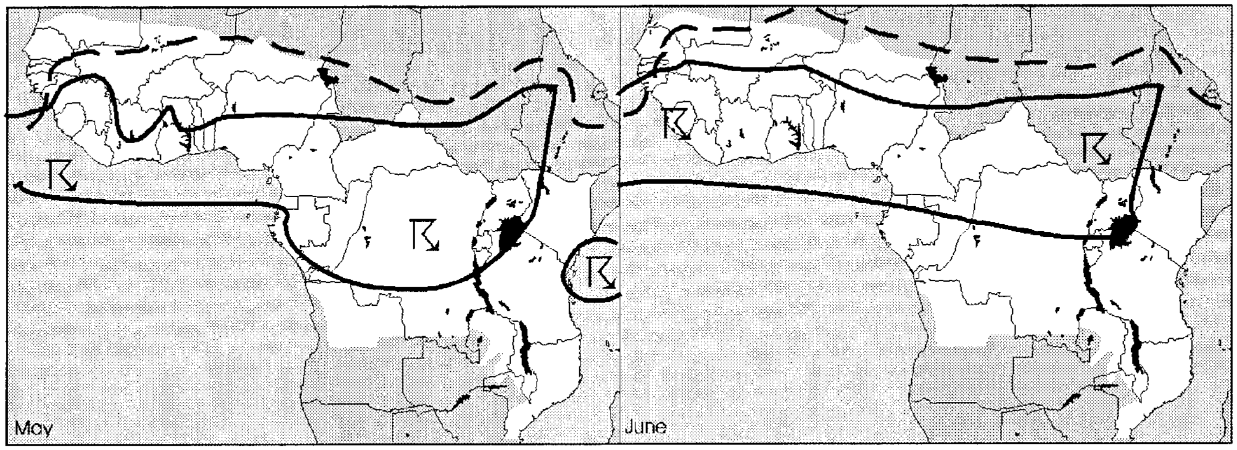


Figure 2-6e. Mean May and June Positions of NET (dashed) and Associated Convection (solid). Convection is at a maximum just off the coasts of Liberia and Cameroon.

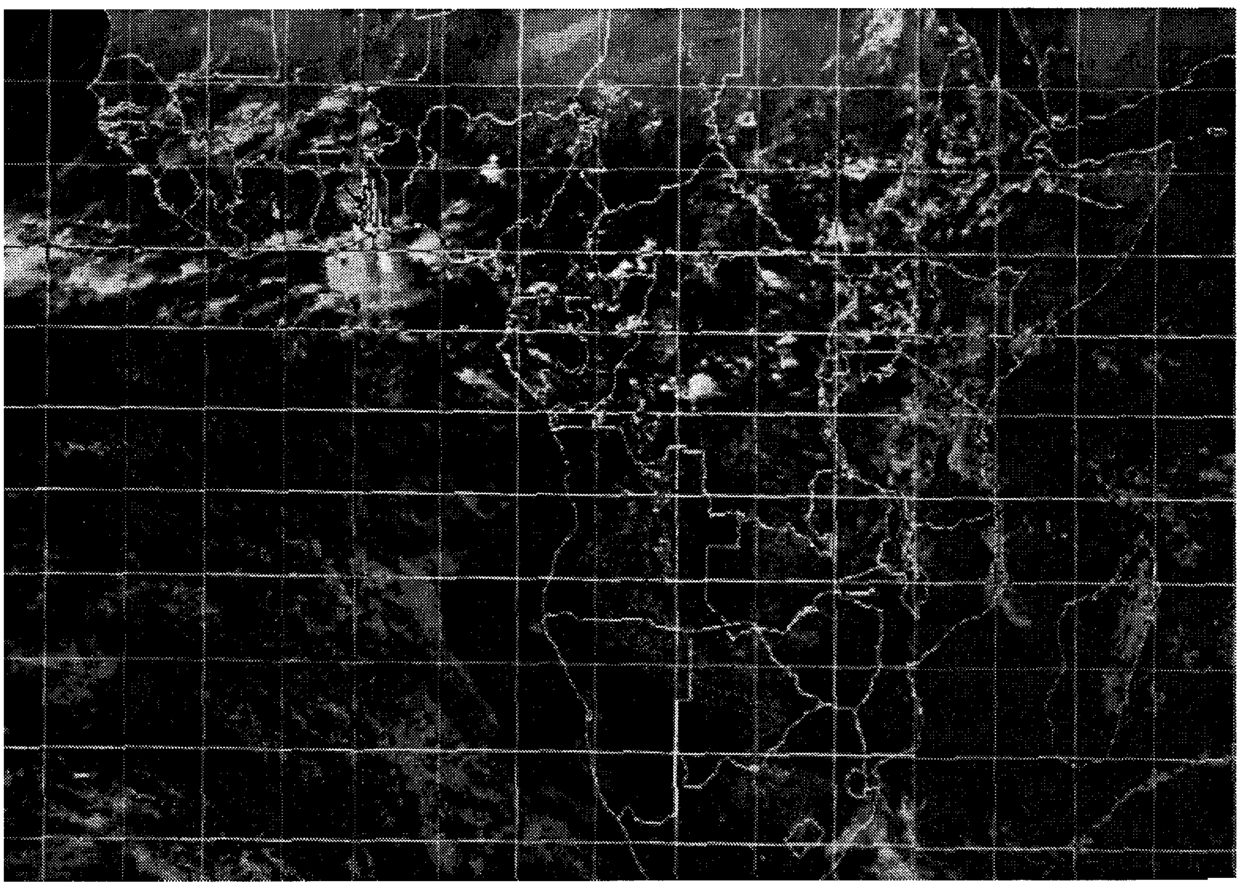


Figure 2-6f. NOAA Visual Image, 22 May 1989. Convection continues to shift northward, starting the wet season over portions of Equatorial Africa (NOAA NESDIS).

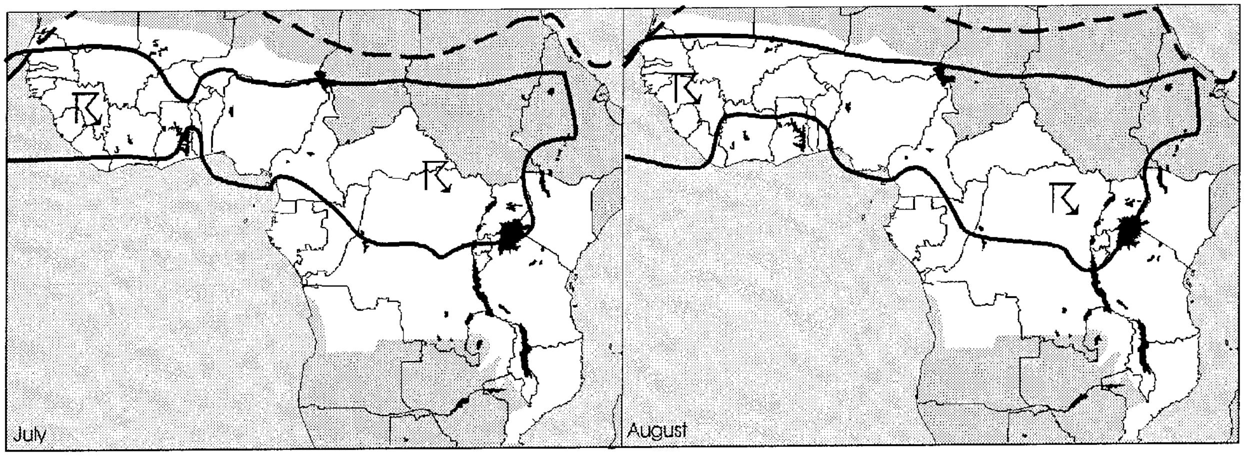


Figure 2-6g. Mean July and August Positions of NET (dashed) and Associated Convection (solid). One convection maximum is over Nigeria and Cameroon; the other is over the Gulf of Guinea.

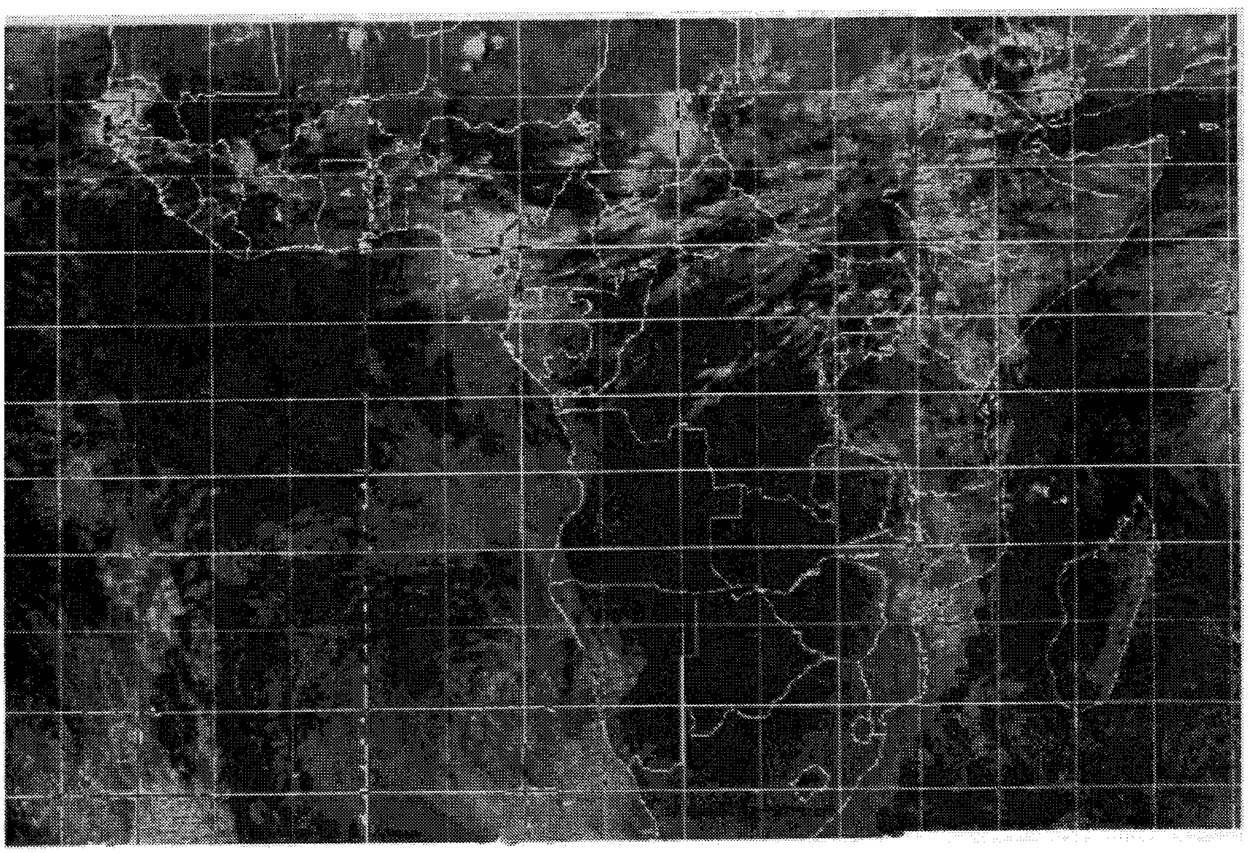


Figure 2-6h. NOAA Visual Image, 28 July 1988. Convection is in the northern hemisphere. The tropical easterly jet produces extensive cirrus blow-off (NOAA NESDIS).

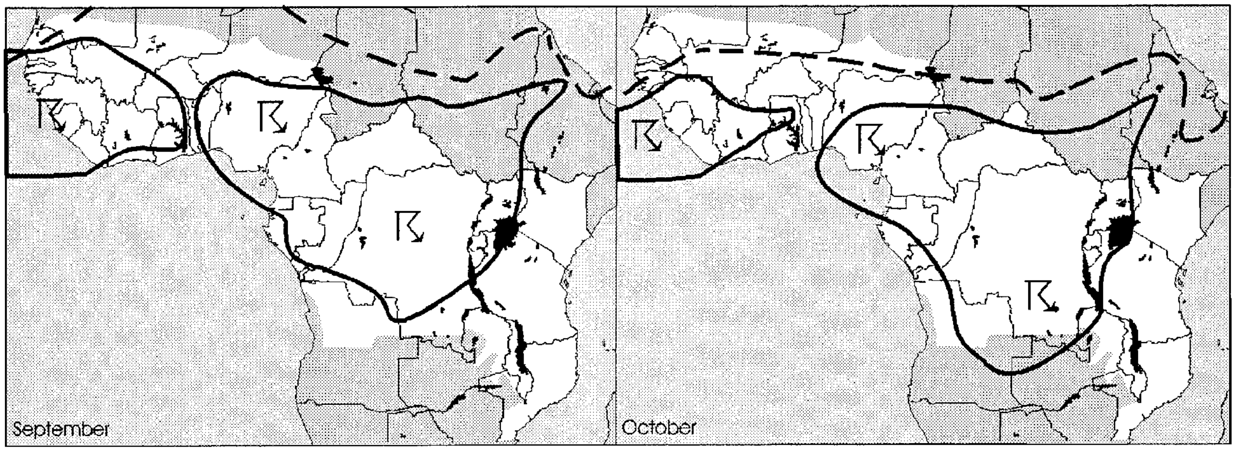


Figure 2-6i. Mean September and October Positions of NET (dashed) and Associated Convection (solid). The convection maximum off the coast of Sierra Leone moved southward; over Cameroon and Zaire, it is off the coast.

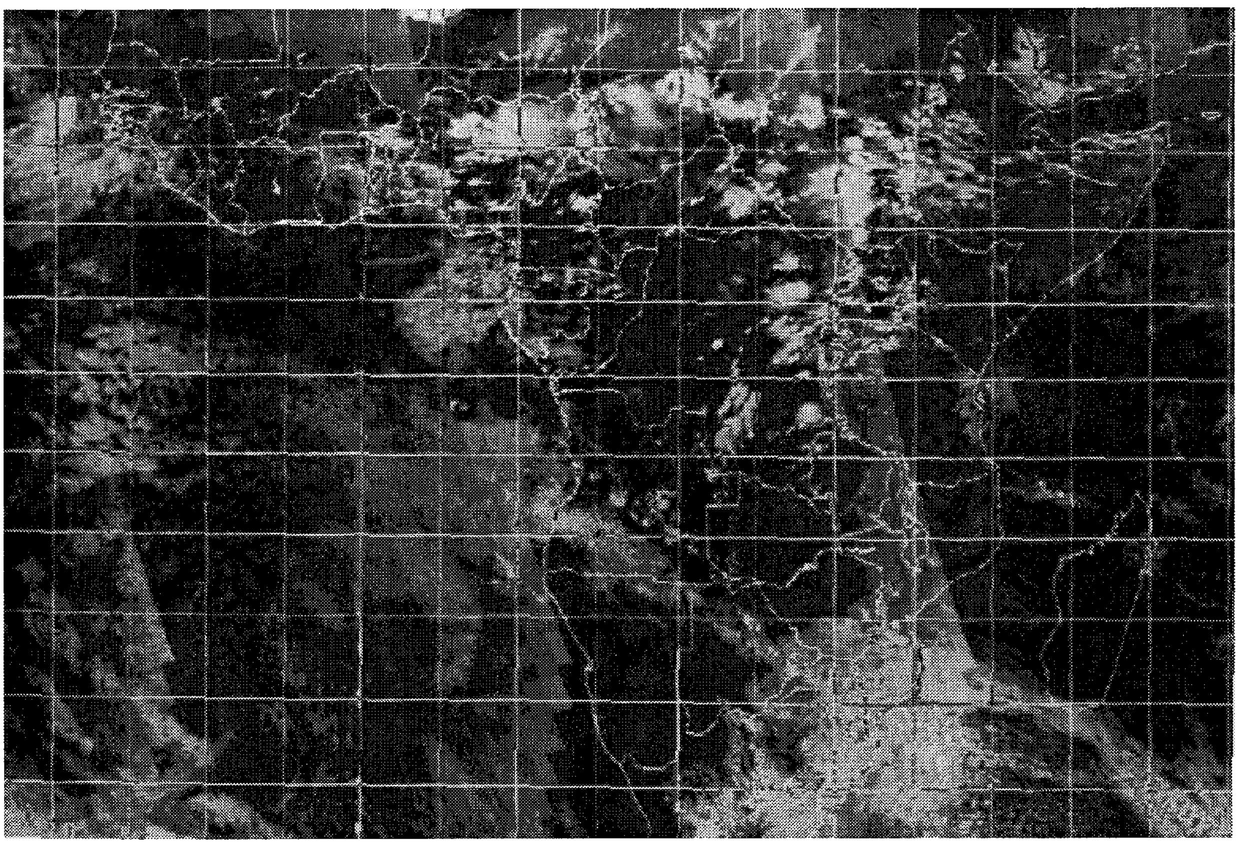


Figure 2-6j. NOAA Visual Image, 2 September 1988. Some convection moves south into Equatorial Africa. A frontal system has moved into the south; onshore flow causes coastal stratus (NOAA/NESDIS).

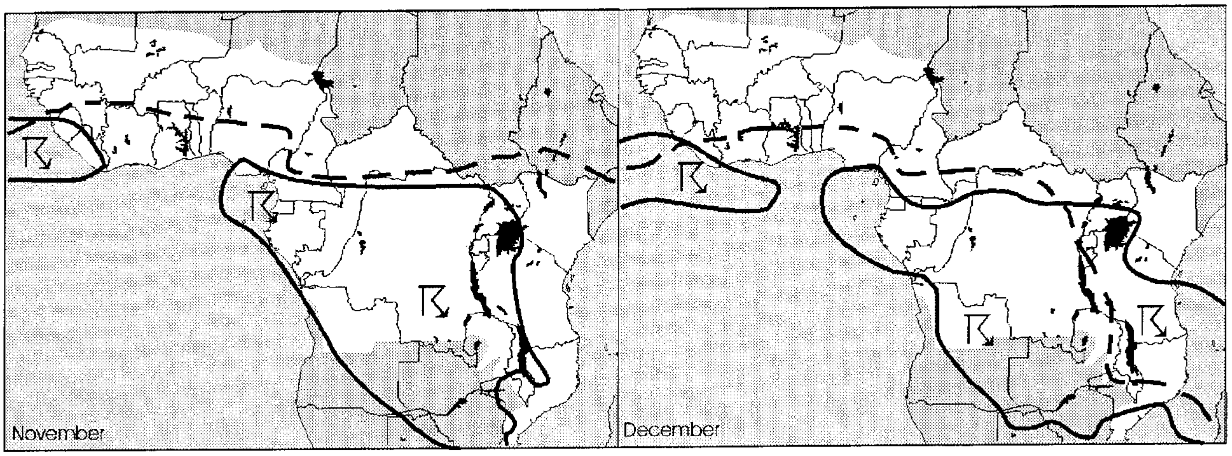


Figure 2-6k. Mean November and December Positions of NET (dashed) and Associated Convection (solid). Convection is again at a maximum near Lake Tanganyika.

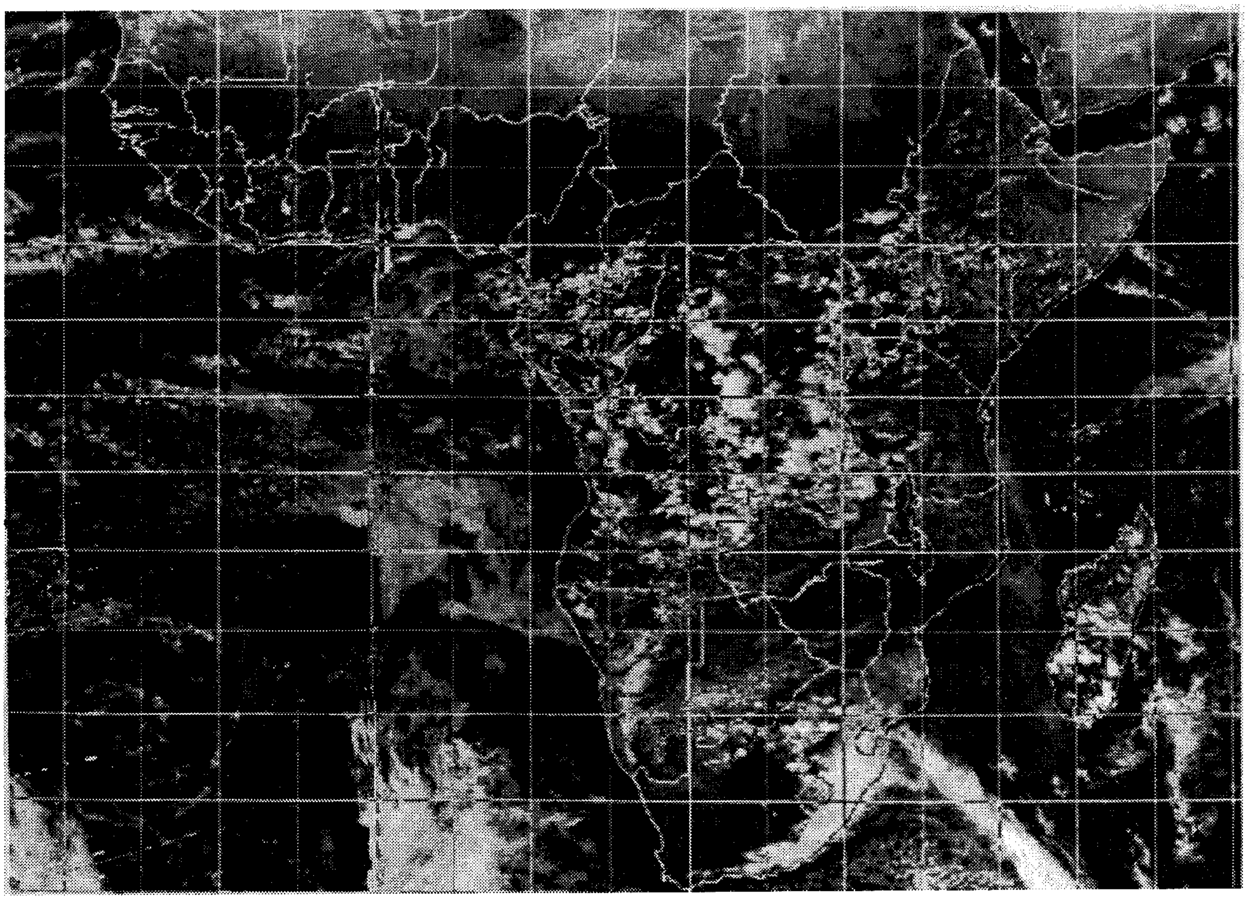


Figure 2-6l. NOAA Visual Image, 15 November 1988. Most of the convection has shifted into the southern hemisphere (NOAA NESDIS).

The Great Rift Heat Trough. This is the local name for another monsoon trough that forms over the Great Rift Valley from the convergence of Northeast Monsoon flow and South Atlantic High outflow from December to March. This trough is oriented generally north-south along the mountain ranges. High terrain enhances lift and convection while making the trough's surface position less well-defined.

The Intertropical Discontinuity (ITD). This is another local name for the NET, actually a monsoon trough that separates the Saharan air mass from the South Atlantic air mass. Note (in Figure 2-7) that the precipitation associated with the NET/ITD (hatched line) occurs well south of the trough's surface position. The labeled "weather zones" (A, B, C, D, and E) will be discussed later. As shown in the figure, the NET slopes southward and extends vertically to about 600 mb. It is a baroclinic zone, with dry, stable Saharan air overriding moist, conditionally unstable, equatorial Atlantic air. Its mean July position is 15° N at 850 mb and 9° N at 700 mb. Its mean January position is 3° N at 850 mb and 7° S at 700 mb.

The NET is marked by wind shifts and humidity contrasts. On its north side, winds are generally northerly to easterly at low- and mid-levels, while winds to the south are southerly to westerly.

The two contrasting air masses also produce the thermally driven North African Mid-Tropospheric Easterly Jet. This jet produces small areas of upper-level divergence, resulting in increasing low-level convergence that enhances cloud cover and rainfall. Weather along this boundary is often broken into zones determined by (1) the depth of the South Atlantic air mass, (2) the instability, and (3) the amount of moisture available. The warm, dry air aloft acts as a cap on the convection. The moist layer must be deep enough to allow convection to develop.

Figure 2-8, next page, shows the general locations of the weather zones shown in Figure 2-7 over West Africa in summer and winter. These zones move northward in the spring at about 180 km a month, and retreat southward in the fall at about 370 km a month. They are evident, in terms of precipitation, eastward to Lake Chad.

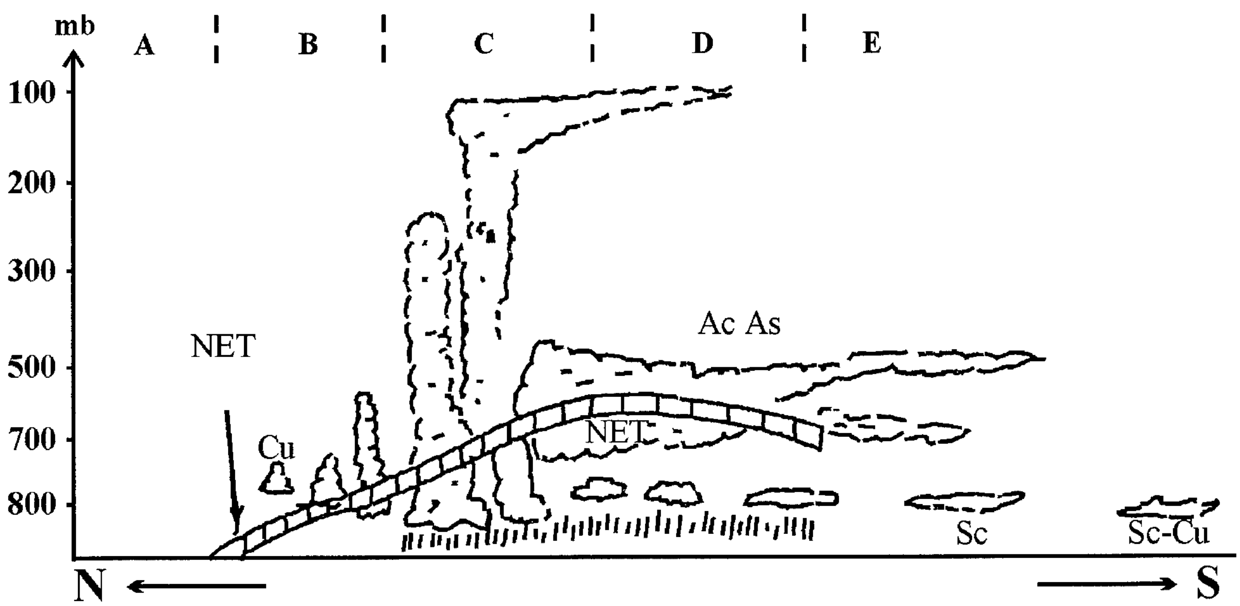


Figure 2-7. Vertical Cross-Section of the NET ("African Interior" Monsoon Trough and Intertropical Discontinuity, ITD)(from Omotosho, 1984). "Weather zones" are indicated by the capital letters at the upper left. Note that some authors refer to Zones C, D, and E as "C1, C2," and "D."

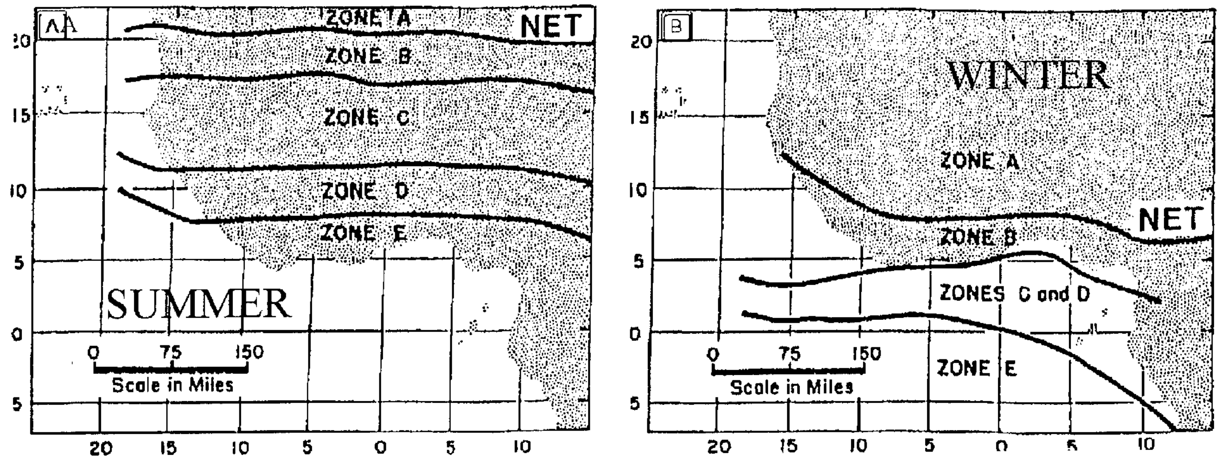


Figure 2-8. General Locations of Weather Zones over West Africa in Northern-Hemisphere Summer and Winter (from Trewartha, 1961).

• *Zone A*, north of the surface monsoon trough, has clear skies with hot, dusty conditions and significant nighttime cooling. Winds are generally northeasterly across the Sahara. Harmattans and Harmattan Haze occur here.

• *Zone B* extends from the surface monsoon trough southward 250 to 450 km. Fair-weather cumulus dominates in the afternoon. Isolated showers and a few thunderstorms (less than five a month) develop, but monthly rainfall is usually under 75 mm because the South Atlantic air mass is shallow, limiting moisture availability.

• *Zone C* is 550 to 750 km wide, but its boundaries are poorly defined, particularly between Zones C and D. The NET is higher and provides more moisture. Precipitation is normally in the form of showers and thunderstorms associated with African Easterly Waves and Squall Lines. Rainfall amounts vary considerably by season and location.

• *Zone D* is 350 to 550 km wide; its boundaries are also poorly defined. Moisture and clouds are abundant. The bands of heavy rain falling in West Africa are sometimes referred to as "monsoon rains." These bands are believed to originate from the poleward surges of storms from the South Atlantic, but this has not been confirmed. Mountainous areas can receive extremely large amounts of rain. Frequent and prolonged precipitation is greatest in this zone, but because it usually originates from middle clouds, it is usually less intense than in Zone C. Thunderstorms are infrequent.

• *Zone E* is normally capped by an inversion at around 2,000 meters (6,700 feet), producing stratocumulus and stratus. Rainfall is less frequent. Zone E coincides with the short mid-summer dry season along the Gulf of Guinea coast.

The Northeast Monsoon originates over the Asian landmass, but the air is modified by either the Arabian Sea or the Ethiopian Highlands before reaching the region. Because the NET is to the south, northeasterly winds affect East Africa and northwestern Madagascar during southern hemisphere summer. The Northeast Monsoon moves into the area from October to December and is strongest in January and February. From March to May, it weakens and is replaced by the Southeast Monsoon. The Northeast Monsoon is normally not as strong as the Southeast Monsoon, but wind speeds are above 50 knots below 2,400 meters (8,000 feet) once every other year near the mountains in Kenya. Figure 2-9 shows mean meridional flow at the equator in January; the Northeast Monsoon is evident along the East African coast, with an average speed of 10 knots.

The Southeast Monsoon develops in response to the large thermal trough over the Asian landmass during northern Hemisphere summer. The flow originates from the South Indian Ocean High, producing southeasterly winds over Madagascar and Mozambique, southeasterly to southerly winds over Tanzania, and southerly to southwesterly winds over Kenya and Somalia. Because of this, countries near the equator refer to it as the "South Monsoon," while countries north of the equator call it the "Southwest Monsoon." Whatever the name, this feature begins in March and moves northward through May as the Northeast Monsoon weakens and the NET moves north. It is strongest from June to September, but usually ends during November as the Northeast Monsoon drives the NET southward. The top of the Southeast Monsoon layer is usually between 3,600 and 4,200 meters. The Somali Jet is present with the Southeast Monsoon. Figure 2-10 shows mean meridional flow at the equator in July; the Southeast Monsoon is evident along the African coast with an average speed of 30 knots.

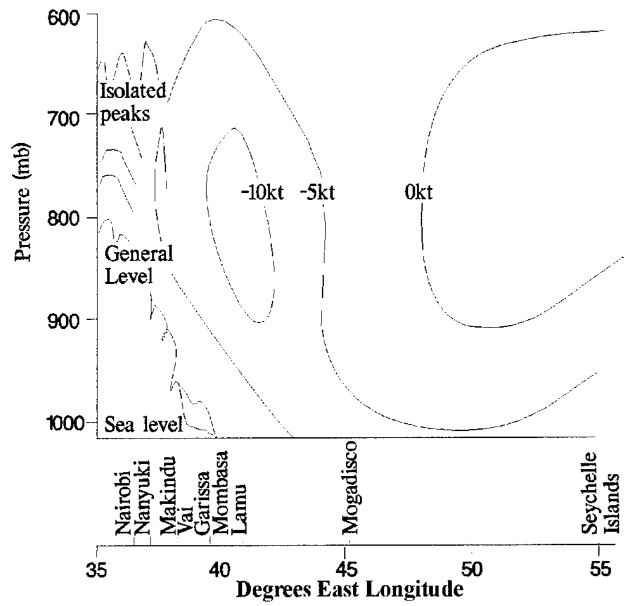


Figure 2-9. Mean Meridional Flow at the Equator in January, Showing the Northeast Monsoon. Negative values indicate flow from the north.

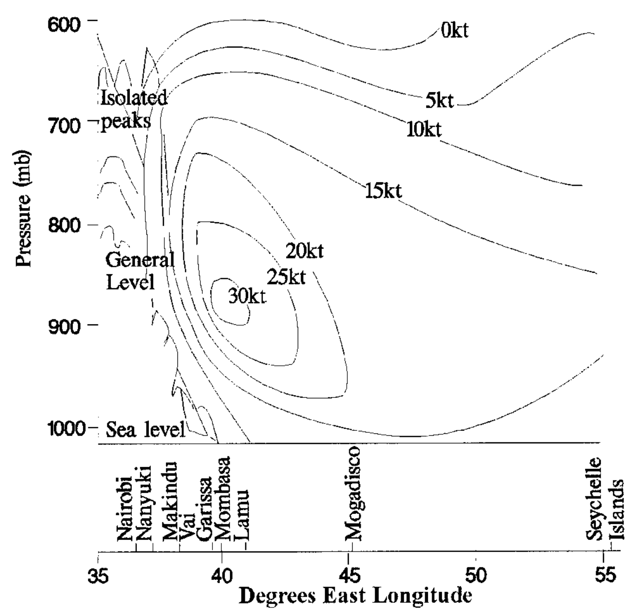


Figure 2-10. Mean Meridional Flow at the Equator in July, Showing the Southeast Monsoon. Positive values indicate flow from the south.

Congo Air Boundary. The Congo Air Boundary (CAB) is produced by convergence of South Atlantic and South Indian Ocean High outflow. It is also called the "Zaire Air Boundary," "Central African Convergence Line," "Inter-Oceanic Confluence," and "African Equatorial Front." Figure 2-11 shows its locations during January, April, July, and October. It technically extends north to the NET, but the Ethiopian Highlands effectively block southeasterly flow and limit the CAB to southern Sudan from April to October. The southern end of the CAB is normally over the escarpment across Namibia and South Africa.

From May to September, the South Atlantic High outflow is cooler and moister than the South Indian Ocean and South African High outflows, both of which are modified crossing the desert interior and the Rift Valley. Hot, dry air flows over South Atlantic air, resulting in stability. The Atlantic air mass doesn't become deep enough to produce precipitation until the NET approaches its northernmost position.

From October to April, instability and precipitation are present, particularly in the Atlantic air mass. The outflow from the South Atlantic High recurves in this season, becoming northwesterly over the Congo River Basin. The Atlantic air mass is warmed crossing the basin, providing the needed instability. Some cloudiness and precipitation occur south of the CAB in the drier Indian Ocean air mass, but it is usually limited to scattered showers. The section of the CAB over the escarpment remains dry year-round.

The seasonal northward movement of the CAB boundary can be gradual or abrupt. Convection gradually stops in some years, but other years see a strong invasion of cold air that drives the CAB northward until the next wet season. The seasonal southward movement has frequent, rapid displacements from the mean position early in the wet season over southern Africa.

In the summer, cloudiness can become oriented more NW-SE, with fronts to the south. Interaction with these frontal systems creates more instability and increased convection for 3 to 4 days over southern Africa. Moist air over Zaire is pulled farther south. If a polar high moves into southern Africa behind the front, CAB convection can be forced northwards.

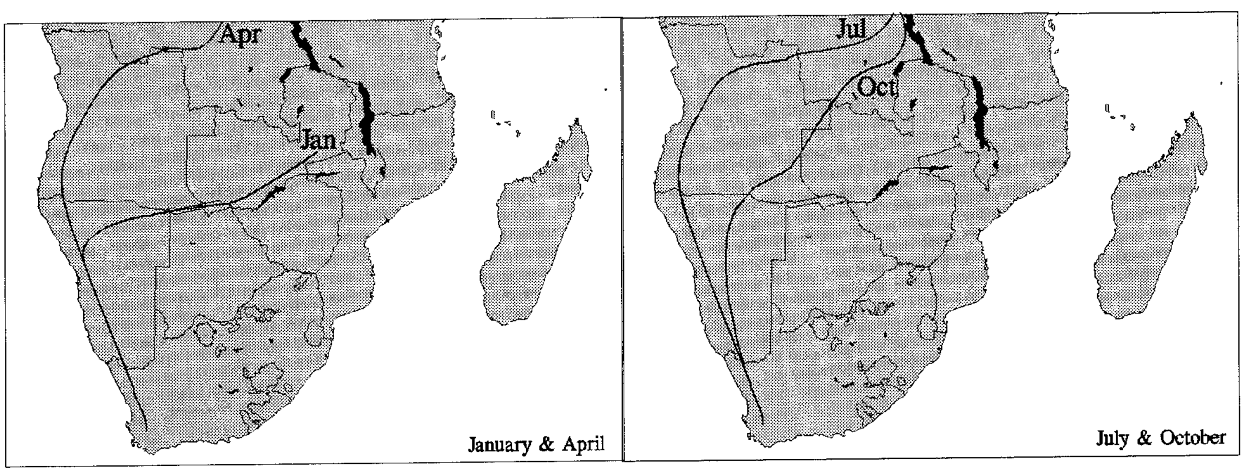


Figure 2-11. Annual CAB Positions. The northeastern end of the January position ends at the NET.

Trade-Wind Inversions. The South Atlantic and Indian Ocean Highs slope toward the equator with height, producing these subsidence inversions over the trade winds. They are strongest over the northwest and southwest coasts of Africa. Relative humidity is greater than 70% below the inversion and less than 50% above. The inversions result in stable conditions, preventing precipitation and trapping moisture in the lower layer.

Mean inversion height along Mauritania's coast is 500 meters, but it rises gradually toward the tropics. The inversion keeps the moisture trapped in the lower layer until reaching the tropics. Areas with strong instability force the inversion higher; heights are usually lower in winter than in summer and lower over water than over land.

Trade-wind inversions also occur over the Southeast and Northeast Monsoons. Mean inversion heights are 1,500 meters over water, rising to 3,300 meters over Nairobi. The wet seasons over East Africa occur during transition seasons as the NET moves north-south across the area.

Jet Streams. The following jet streams affect Equatorial Africa:

Polar and Subtropical Jet (PJ and STJ). The PJ's positions and movements control cold air advection and mid-level direction for developing cyclones. The STJ provides steering, shear, and outflow in the upper levels. Figure 2-12 shows mean jet positions for January and July.

Mean PJ positions vary over Europe from 55 to 65° N. Maximum wind speeds from December to March vary from 60 to 160 knots, becoming lighter in summer. The PJ is usually found near 300 mb (9 km) MSL, but slightly higher in summer. Southward deviations to 30° N are most frequent between December and March, but they can occur as late as June. Initially, surface low-pressure cells develop when a strong PJ digs south of 30° N and forms a deep upper-level trough. Northerly flow often develops on the east side of a blocking high-pressure ridge over the eastern Atlantic. The PJ and upper-level trough may intensify surface lows over the Mediterranean and in the lee of the Atlas Mountains in northwestern Africa. Northerly flow can move the flow eastward with the cold front/shear line reaching as far south as 10° N over central Africa. Although the STJ shows less variability in its daily position, seasonal variability is greater than the PJs. STJ winds are normally west-southwesterly. Mean STJ positions over the subtropics range from 22 to 45° N; its southernmost position over West Africa is in February. The STJ can reach 15° N during the winter, especially over Mauritania, Senegal, and Mali. Maximum speeds between December and April are between 80 and 180 knots at a mean height of 200 mb (11.7 km) MSL. Speeds between May and November are between 30 and 60 knots from 11.7 to 12.9 km MSL. The STJ is weakest in July and August, when it seldom extends south of 35° N.

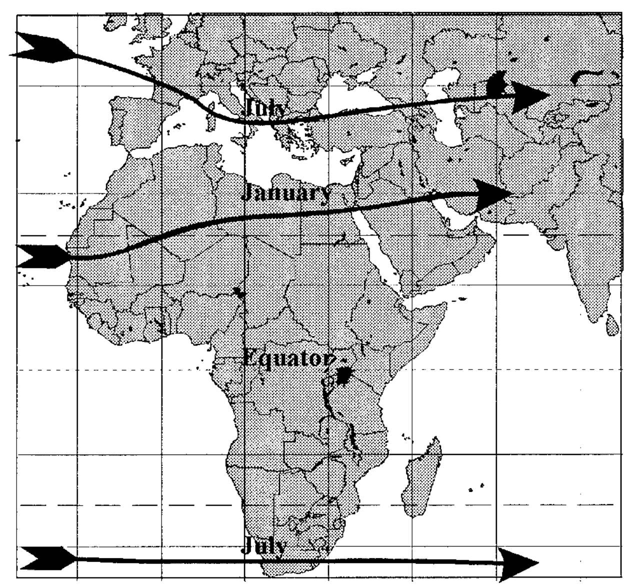


Figure 2-12. Mean Positions of the Subtropical Jet (STJ). There is no mean STJ in the southern hemisphere in January.

Southern-hemisphere jet streams are quite different from those in the northern hemisphere in that there is just one band of maximum winds during most of the year. Southern-hemisphere jets seldom reach far enough north to affect even the region's southernmost areas.

Tropical Easterly Jet (TEJ). This northern-hemisphere summer jet in the upper-level easterlies develops at 200 mb as outflow from the southern edges of the Tibetan Anticyclone; it provides an outflow mechanism for monsoon trough convection over Sub-Saharan Africa. Changes in the TEJ can cause surges in convection. Its mean position is at about 10° N, 4-5 degrees south of the surface monsoon trough, but it oscillates between 5 and 20° N (see Figure 2-13). Speeds exceed 100 knots between 100 and 200 mb.

A band of upper-level easterlies is present year-round over Africa, but they are weak and are not technically "jet streams" without the Tibetan Anticyclone outflow. In February, the center reaches 10° S, with speeds averaging 35 knots. During transitions between seasons, the center is near the equator at from 10 to 20 knots.

North African Mid-Tropospheric Easterly Jet (MTEJ). This mid-level jet occurs over subtropical Africa between May and October. It develops from the thermal contrast along the NET as hot, dry Saharan air rides over the cooler, moister equatorial air. The gradient is strongest during the summer when surface temperatures reach their maximum over the Sahara, but it change little over equatorial regions. The MTEJ steers African Waves and Squall Lines westward. It is important in the development of African Squall Lines and also produces localized areas of divergence, enhancing cloud cover and rainfall.

The MTEJ also develops along the Ethiopian Highland foothills with the southeasternmost penetration of Saharan air, and extends westward to the Atlantic Ocean. Mean jet core winds average 25 knots; maximum speeds reach 50 knots. Figures 2-14 and 2-15 (opposite) show cross-sections of the MTEJ in July and August, respectively. The easterly wind maximum correlates well with the NET'S mean August height at 13° N.

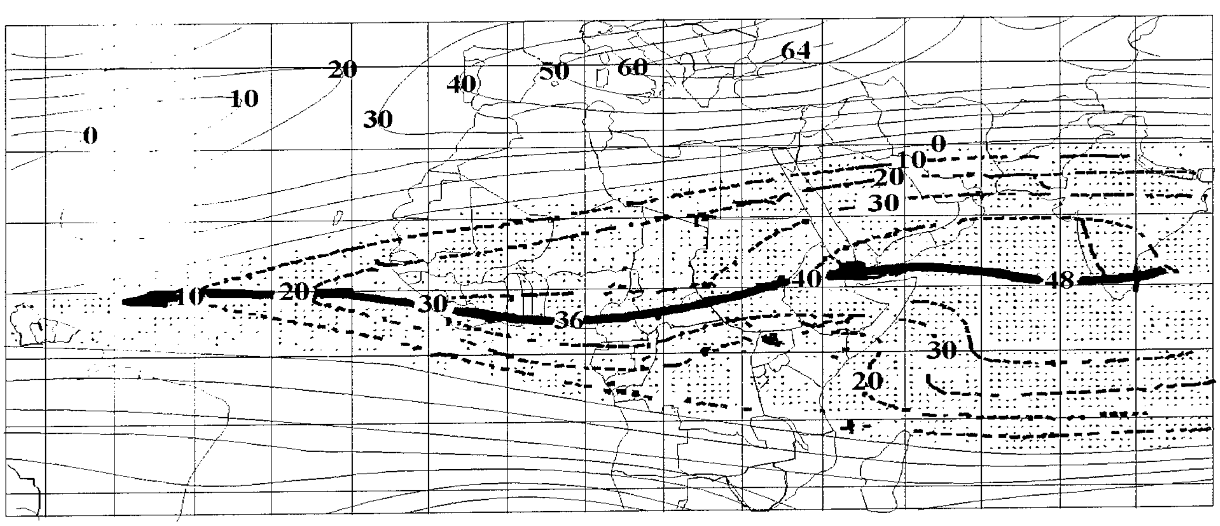


Figure 2-13. Mean July 200-mb Zonal Flow, Showing the Tropical Easterly Jet (arrow). The stippled area represents easterly flow. The dashed lines are *easterly* isotachs, in knots; the solid lines are *westerly* isotachs.

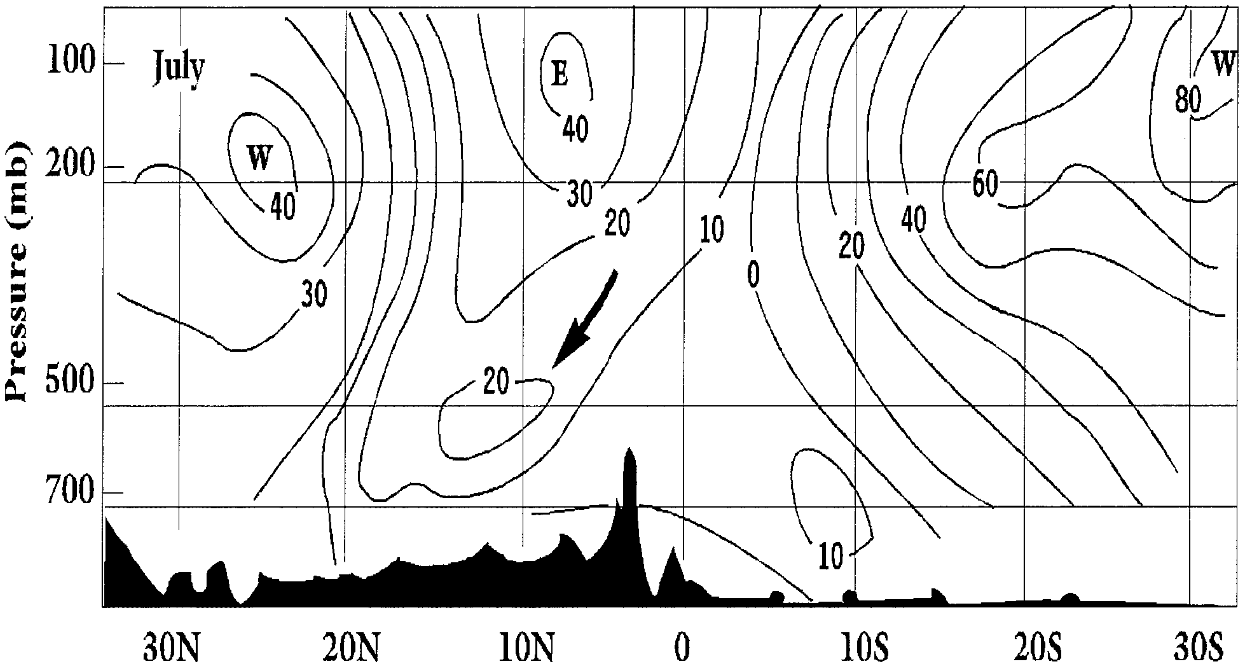


Figure 2-14. North-South Cross-Section of Zonal Winds Near 10° N in July. The solid lines are isotachs, in knots. The arrow represents the MTEJ.

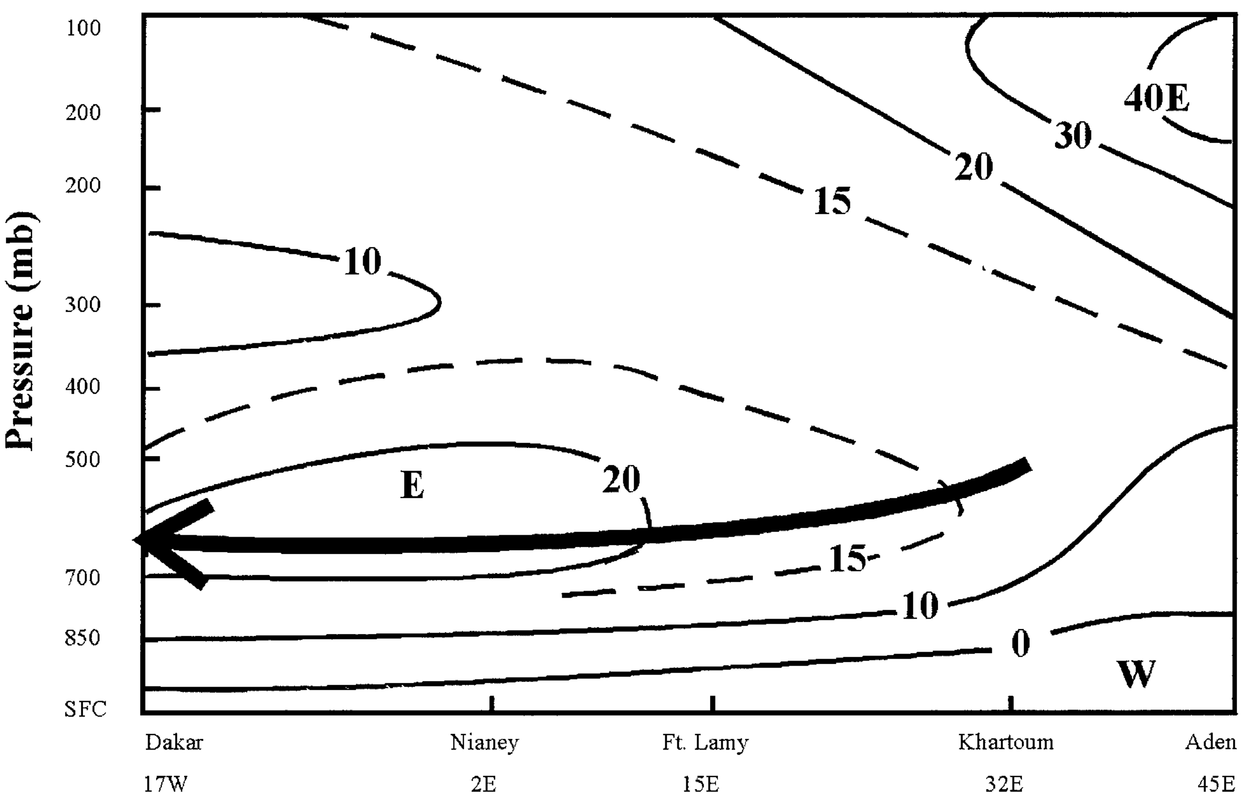


Figure 2-15. West-East Cross-Section, Showing the MTEJ (arrow) at 13° N in August (from Burpee, 1972).

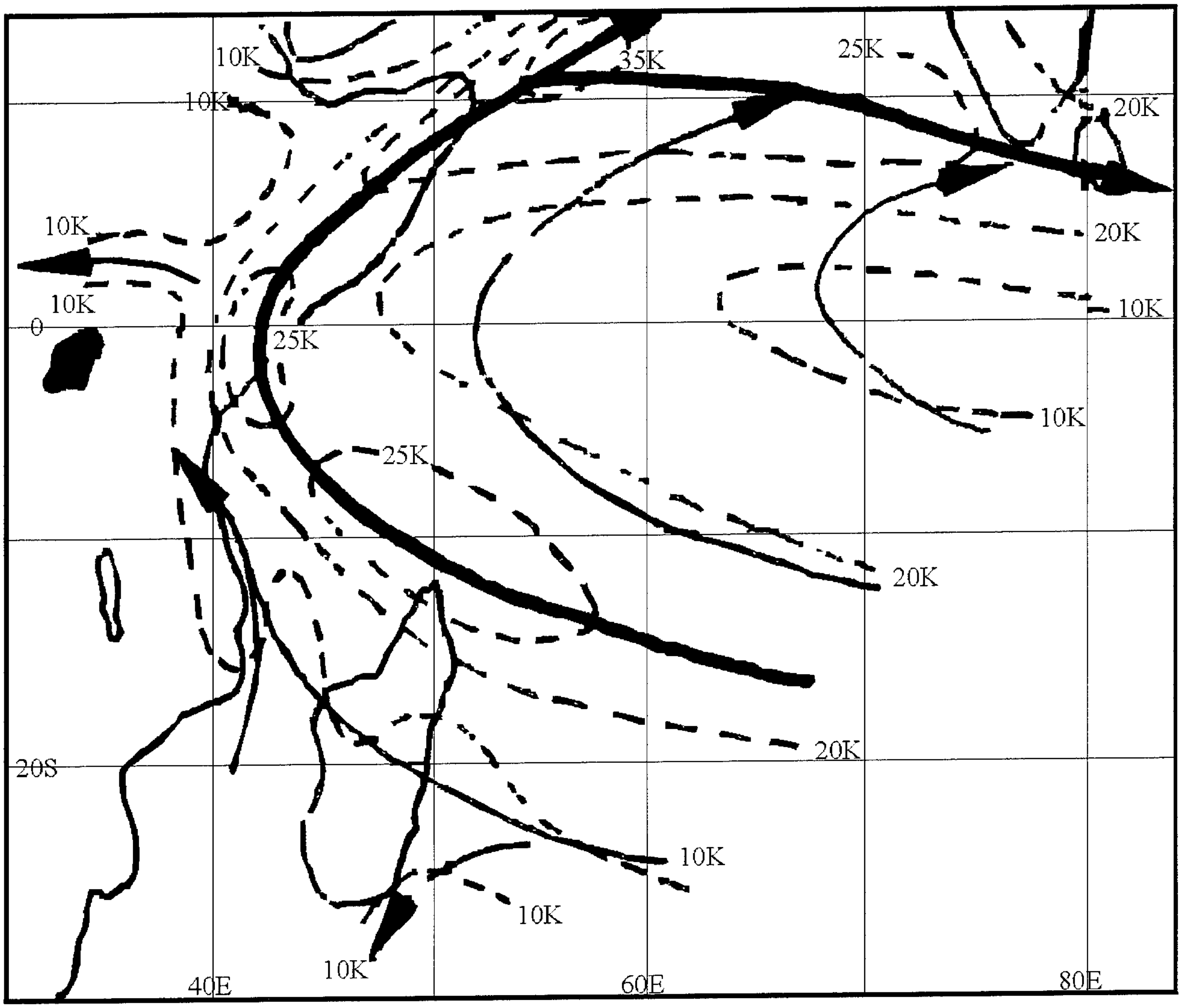


Figure 2-16. Mean July Airflow at 900 Meters. The solid lines are streamlines; the thicker line indicates the mean jet core. Dashed lines are isotachs, in knots.

Somali (East African) Jet. From April to late October, Southeast Monsoon flow from the South Indian Ocean High is compressed into a high-speed jet core along the eastern edge of Africa. This core normally passes just north of Madagascar heading to the northwest, enters Africa over southern Kenya, and turns to the northeast out across Somalia. The core is usually at about 600 meters MSL over the open Indian Ocean. Over land, the jet is normally between 1,200 and 2,100 meters MSL. Figure 2-16, above shows mean July airflow directions and speeds at 900 meters across the western Indian Ocean basin.

The Somali Jet's mean core speeds are between 25 and 40 knots. It normally strengthens from April to July and gradually weakens from August to October. Highest wind speeds are near the equator across Kenya and Somalia; speeds of 100 knots have been reported, probably due to southern-hemisphere polar surges.

Figure 2-17 (opposite) shows the maximum wind speeds associated with the Somali Jet that have been reported across the area between 600 and 2,400 meters MSL.

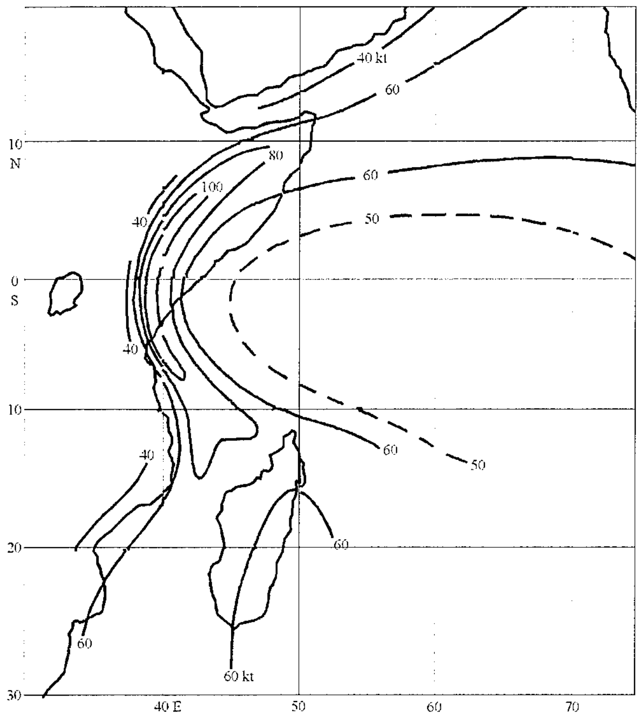


Figure 2-17. Maximum Wind Speeds Associated with the Somali Jet (knots).

The core of the Somali jet is usually 550 to 900 km long, 180 to 370 km wide, and 2 km deep. Height and speed variations in single or multiple low-level jets are primarily produced by synoptic-scale surges. Several branches often form south of the equator, but they are normally compressed into one near the equator. Individual cores can be tracked moving downstream through the region, data permitting, and can cross Madagascar and Kenya within 24 hours.

Figure 2-18 shows a vertical cross-section of the jet across Kenya on 13 June 1966. Strong wind shear is present outside the core, producing moderate turbulence.

Like most low-level jets, the Somali Jet shows a marked diurnal variation. Peak core speeds are near dawn, with minimum core speeds in late afternoon. Surface wind speeds beneath the core are just the opposite; minimum speeds are at dawn and maximum speeds are in the mid-afternoon.

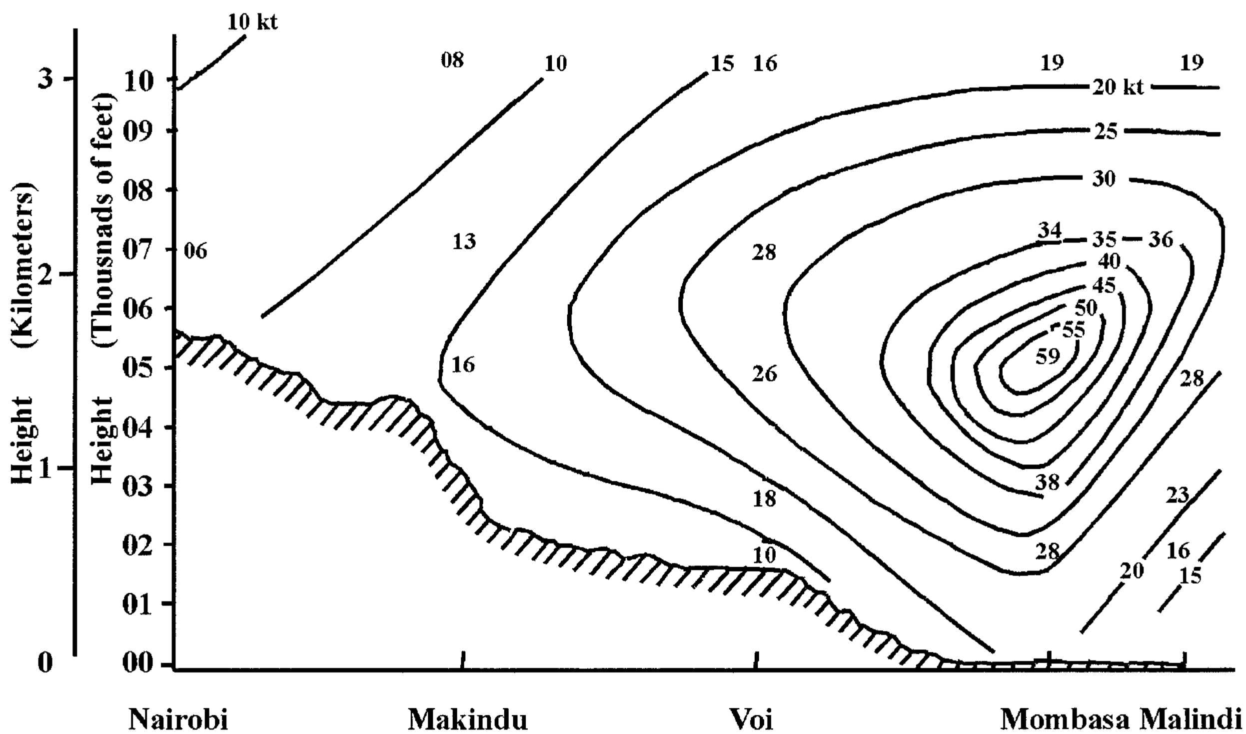


Figure 2-18. Vertical Cross-Section Over Kenya, 13 June 1966.

Mid- and Upper-Level Flow Patterns. Figures 2-19 through 2-22 on the following pages show January, April, July, and October streamline flow at 850, 700, 500, 300, and 200 millibars over the entire study area. The 850-mb level is usually used as the surface across the interior plateaus of southern Africa.

The Subtropical Ridges are upper-level features north and south of the equator over Africa with easterly flow between them. Moving north-south with the sun, they are at their northernmost positions in July, and at their southernmost positions in January. These features are important because they provide outflow for the NET convection. See Figures 2-19 through 2-22, 200 mb, for the locations of the southern-hemisphere ridges.

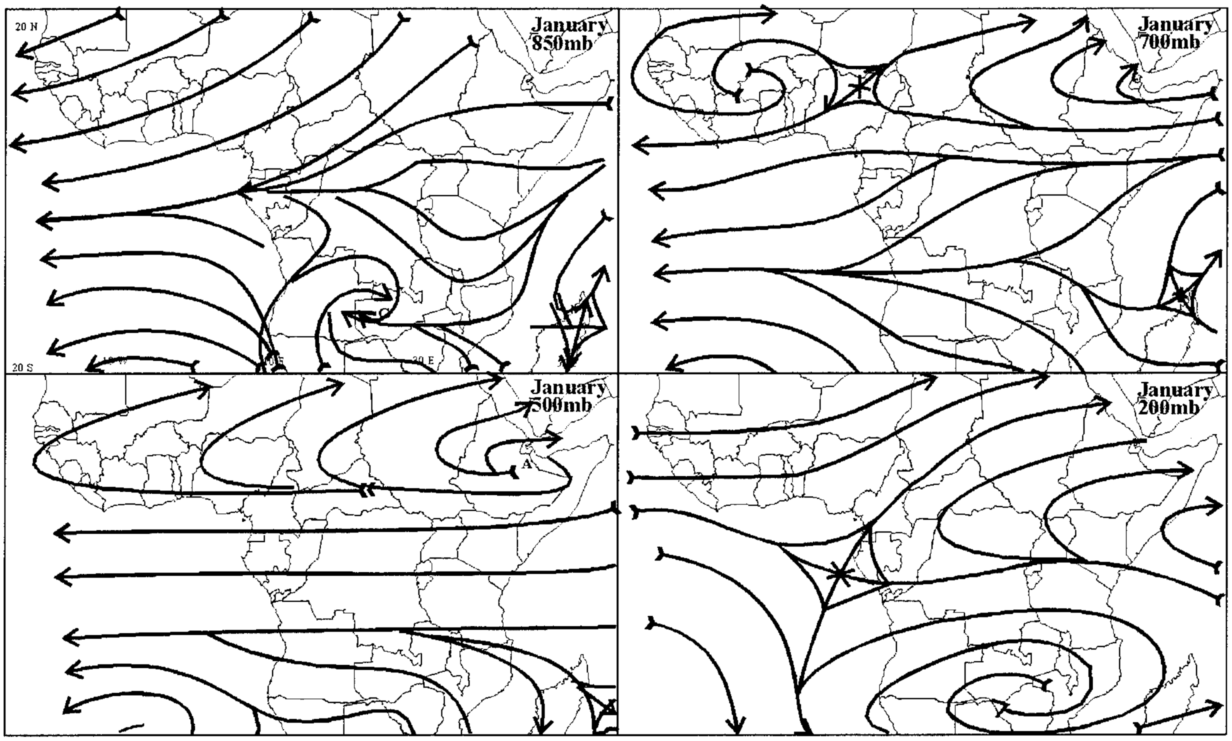


Figure 2-19. Mean January Upper-Air Flow Patterns at 850, 700, 500, and 200 mb.

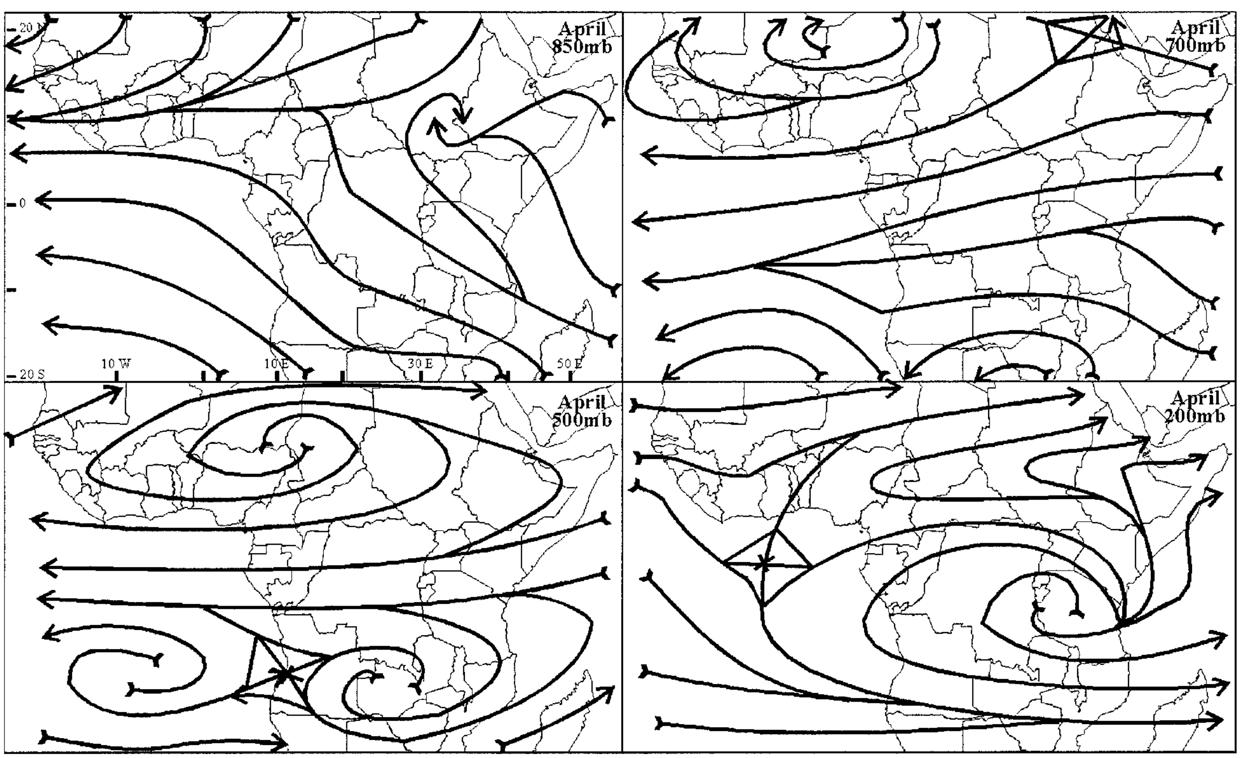


Figure 2-20. Mean April Upper-Air Flow Patterns at 850, 700, 500, and 200 mb.

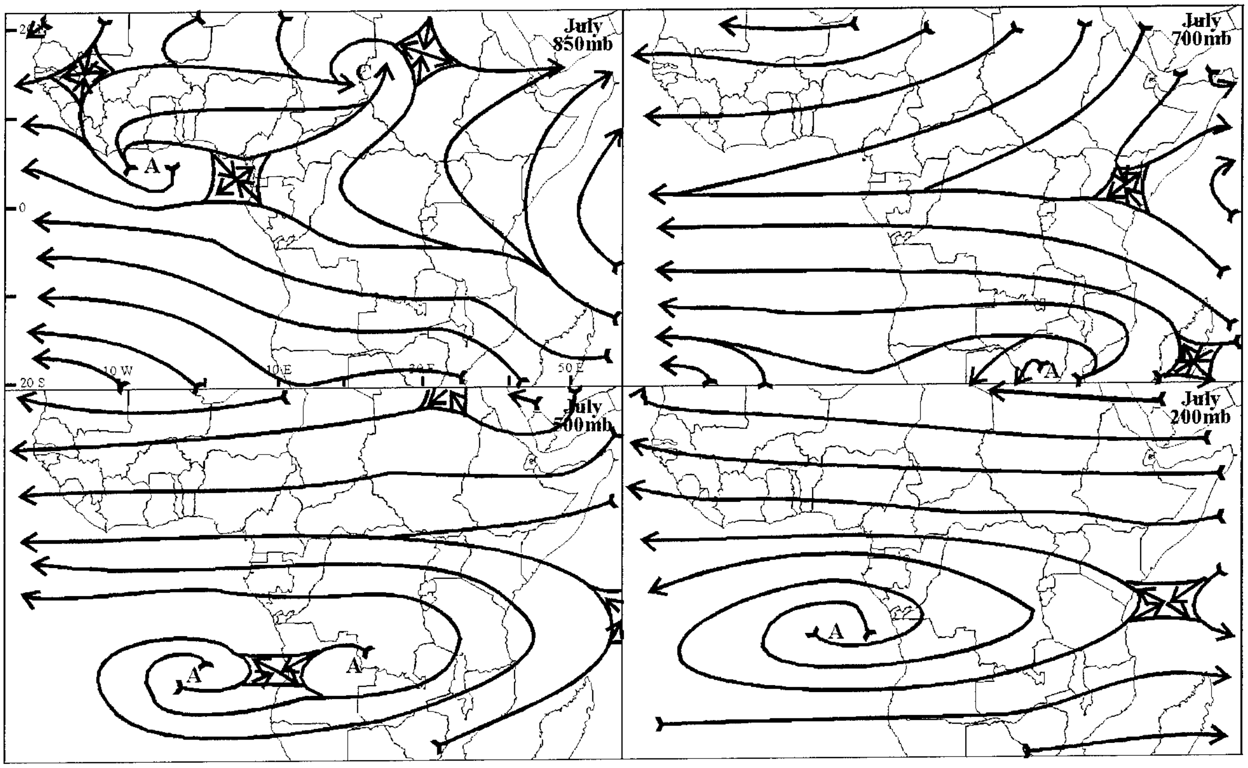


Figure 2-21. Mean July Upper-Air Flow Patterns at 850, 700, 500, and 200 mb.

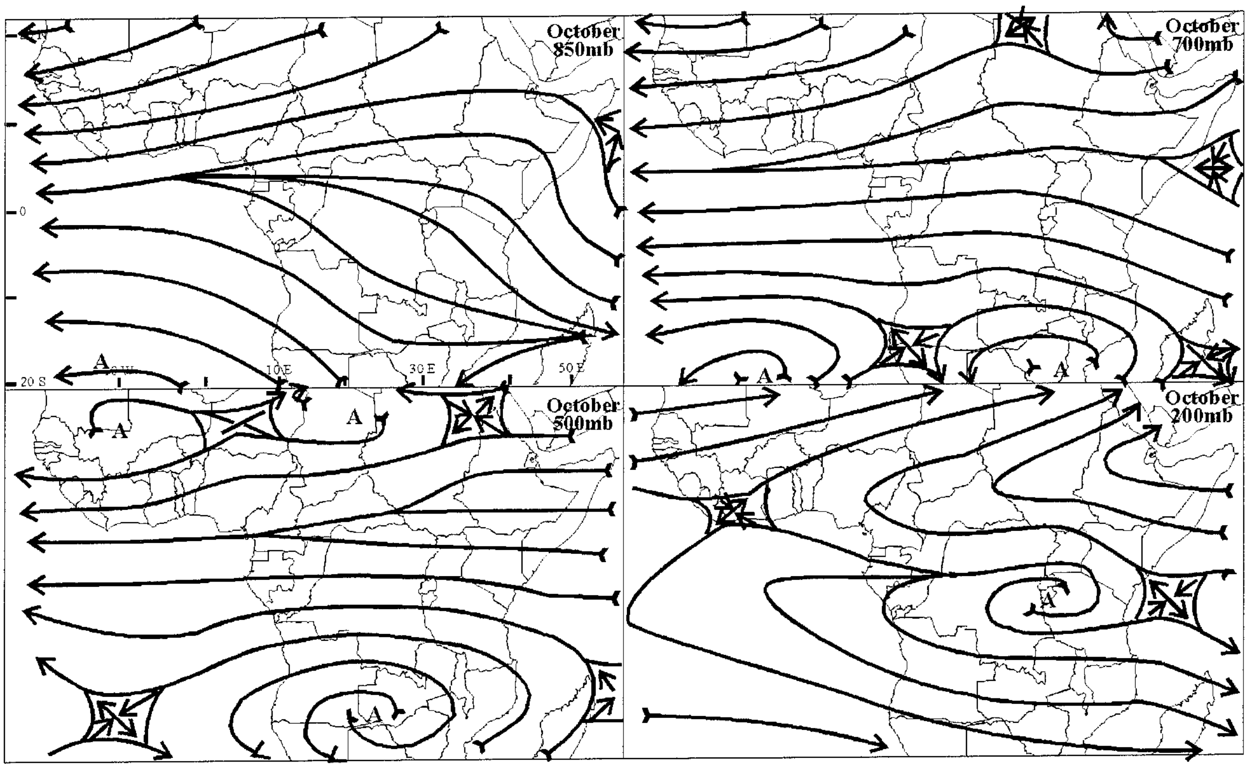


Figure 2-22. Mean October Upper-Air Flow Patterns at 850, 700, 500, and 200 mb.

Mid-Latitude Cyclogenesis/Storm Tracks.

Atlas Lows can develop from October to June with peak occurrences in March and April. They originate in the north-central interior of Algeria southeast of the Atlas Mountains near 30° N, 2° E. Atlas Lows generally form when a mid- or upper-level trough, oriented NE-SW over Spain, is positioned over a weak surface low or a slow-moving cold front.

In March and April, the mean Azores High moves northwestward, shifting the mean mid-level flow pattern from zonal toward meridional. This can cause a southward movement of disturbances along the Polar Jet (PJ), which often digs along the backside of the 500-mb trough, producing lifting along the Atlas Mountains. Mid-level cold air and moisture cross the mountains as a cold-core cut-off low or short wave. These storms seldom develop or penetrate very far into the Sahara without strong northerly flow and mid-level cold air support. The Subtropical Jet (STJ) provides strong outflow and divergence aloft; mean spring wind speed is 80 knots over western Africa.

The preferred area for low-pressure center intensification is under the southeast quadrant of the upper-level trough. The low often deepens in the area between the two jets. Jet-stream interaction occurs most frequently with Atlas Lows between 25 and 30° N, nearest the mean position of the STJ.

Figure 2-23 illustrates this PJ/STJ interaction and shows the usual low-pressure formation area for Atlas Lows; it also shows the primary and secondary tracks of the Atlas Lows, which normally move northeast over the south-central Mediterranean along the polar-subtropical jet axis. When a sustained northerly flow pattern persists for more than 3 days, the PJ and the mean Atlas Low track shift southward. The lows move east across the northern Sahara and polar air surges south of 30° N. Strong surface high pressure normally moves in behind the system, producing duststorms and sandstorms (see "Harmattan"). A well-defined surface front can produce a "wall of sand."

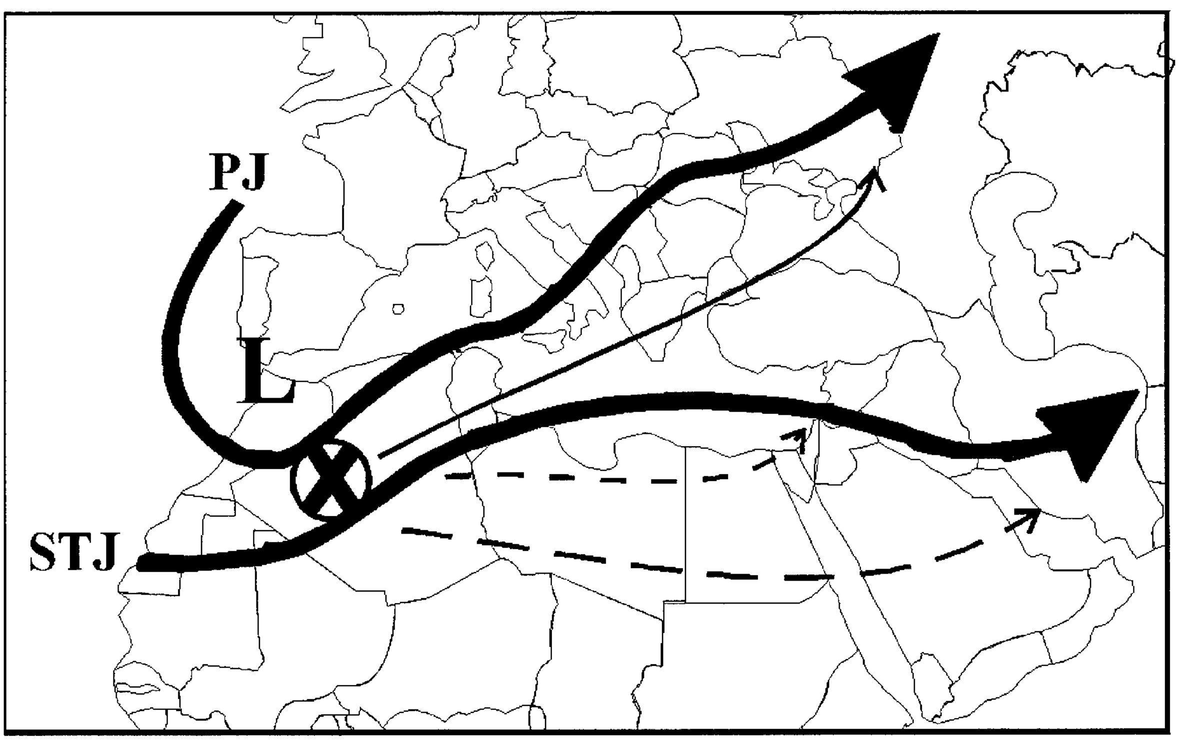


Figure 2-23. Typical Jets (large arrows) During Atlas Low Development. The circled "X" represents the surface low development area, while the "L" marks the jet-level low. The small arrows are the primary storm tracks; the dashed arrows are the secondary tracks.

Figure 2-24 shows an Atlas Low developing and crossing the Sahara. The farther east they travel across Africa, the farther fronts can penetrate south, primarily due to the increased distance from the Azores High. In extreme cases, fronts have reached 15° N across Mauritania, Mali, and Niger. Farther east, there is evidence they may have reached northern Nigeria, Cameroon, and the Central African Republic.

Moisture is normally limited to the mid- and upper-levels as the STJ advects the upper-level moisture. A lower deep, dry layer has to become saturated before any rain reaches the surface, but this only occurs with strong systems. Although uncommon, fronts are occasionally able to tap low-level moisture from the Atlantic. When they do, significant rains fall along the west coast (from Mauritania to Guinea) and in higher terrain. Coastal countries can receive 1 to 3 inches, but less than an inch falls in Mali. These rains are more often stratiform than convective.

South Atlantic Lows. At their strongest, these southern-hemisphere, mid-latitude systems can affect Equatorial Africa. Their associated fronts in the winter have penetrated northward to 10° S over central and eastern Africa, reaching Zambia and Tanzania. In the summer, fronts rarely make it north of 25° S. The west coasts of Angola and Namibia are rarely affected due to the presence of the South Atlantic High. Two to three fronts a year reach Zambia, but in some years there are none at all. Malawi gets rain from these fronts because of higher terrain that produces lift. Cold fronts moving northeast towards Mozambique weaken as warm ocean currents modify the air mass; the frontal boundary is frequently evident aloft, but not at the surface. Three to four fronts a winter reach central Mozambique.

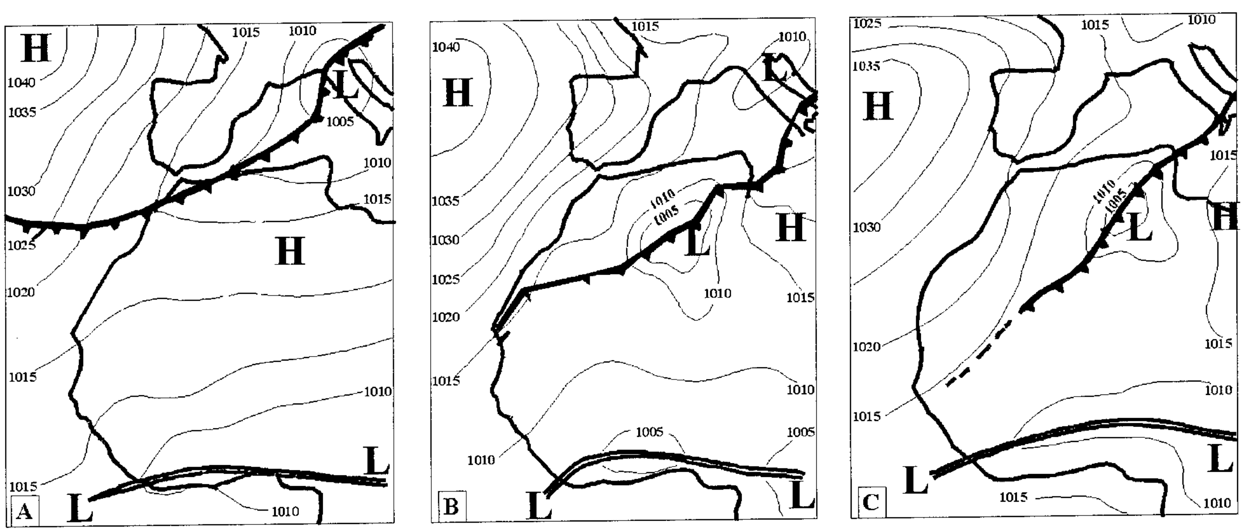


Figure 2-24. Atlas Low Development Sequence. In "A," a cold front reaches northwest Africa with a strong high behind it. In "B," the low develops along the existing front with a strong high moving south behind it. In "C," the low is shown traveling east across the Sahara as a weakening cold front reaches the Sub-Sahara (From Leroux, 1983).

Southern Hemisphere Polar Surges between May and October produce fluctuations in the Somali Jet over East Africa. Frontal systems can temporarily displace the South Indian Ocean High, cutting off the normal flow pattern, while strong high pressure behind the system can produce surges of low-level flow through the Mozambique Channel. Generally, the frontal boundary does not cross the equator, but "surges" in the flow do. Surges can produce sudden increases in cloudiness and precipitation. Figure 2-25 shows a case of a strong Somali Jet and Southeast Monsoon flow, while Figure 2-26, next page shows the "surge" episode that occurred shortly thereafter.

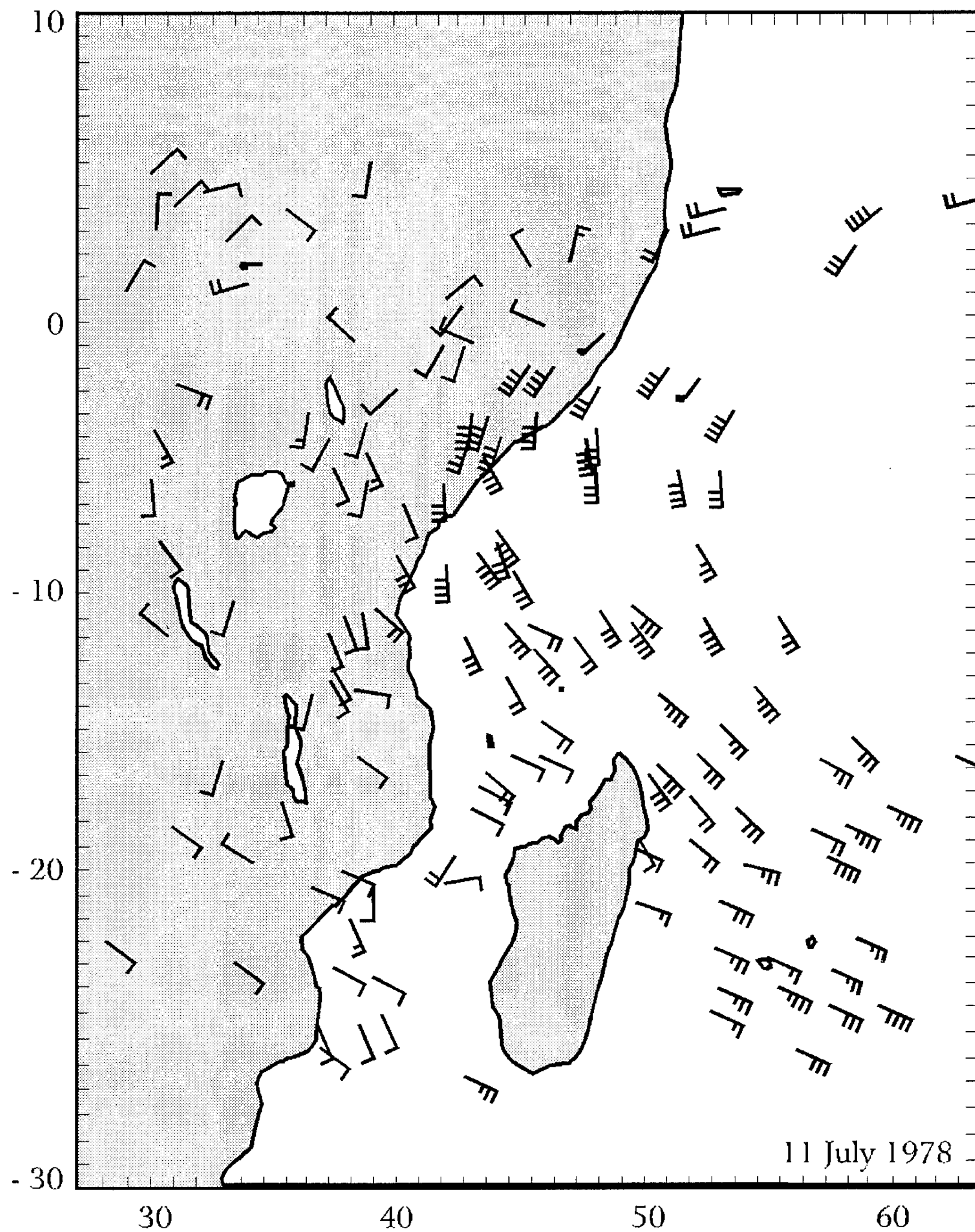


Figure 2-25. Strong Somali Jet, 11 July 1978. The Somali Jet is producing winds of 50 knots. The South Indian Ocean High is firmly established at 37° S, 56° E, providing the southeasterly flow into the jet from west of Madagascar.

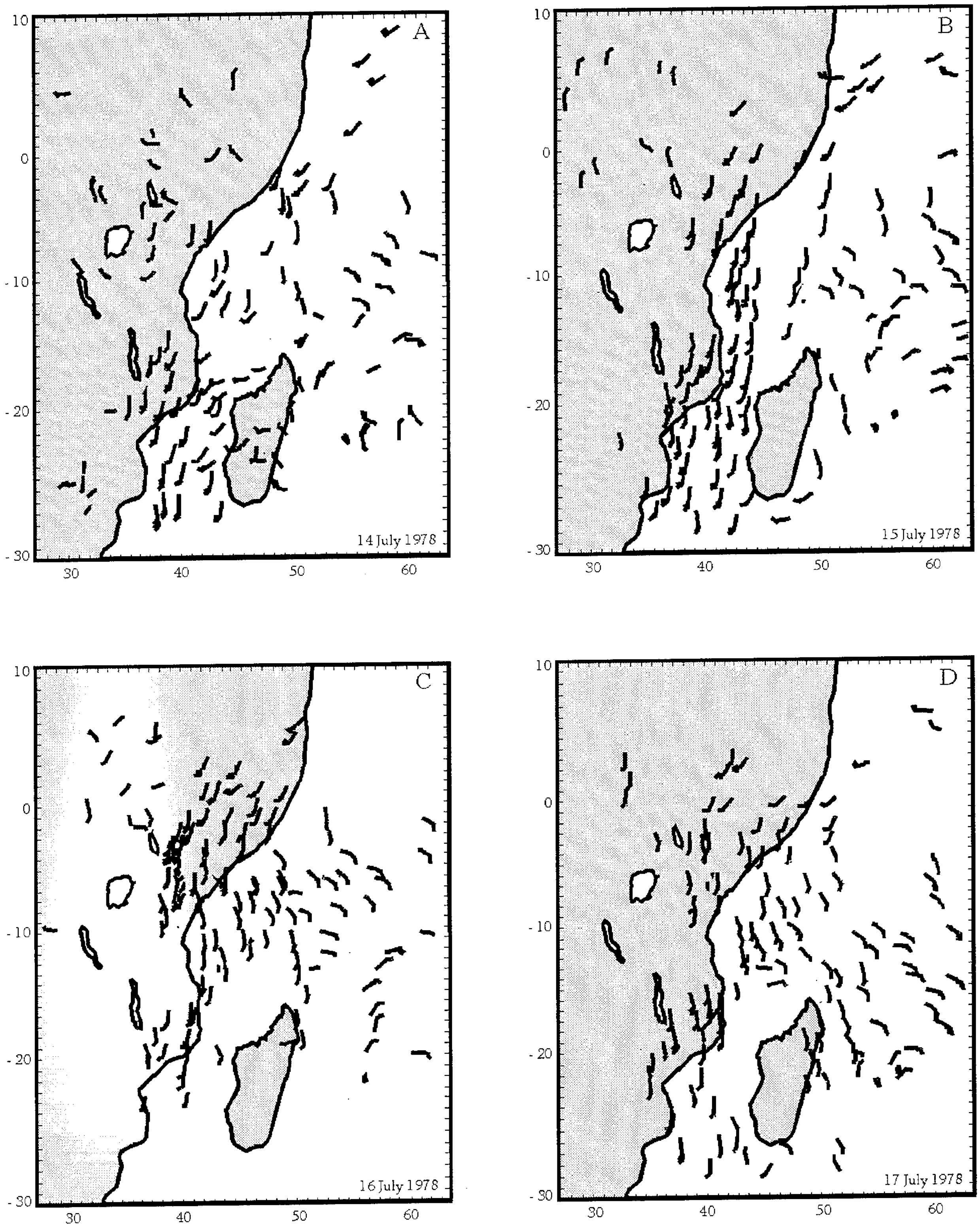


Figure 2-26. Polar Surge, 14-17 July 1978. Satellite-derived wind vectors from Cadet and Desbois, 1981.

Subtropical Cyclones, also known as "Monsoon Mid-Tropospheric Lows," can develop in the South Indian Ocean and move northwestward into East Africa from July to September; from July to April, they can move westward into South Africa. These lows develop when a cold pocket is cut off equatorward of the polar westerlies. They produce convection and heavy rainfall, with the heaviest bands of rain and convection and the strongest surface winds found several hundred kilometers from the center. Circulation is strongest at the mid-levels; cyclonic circulation seldom extends to the surface. Latent heat release through deep convection sometimes provides enough warming to create the appearance of a tropical cyclone circulation and, given time, can actually change the low into a tropical cyclone.

Subtropical cyclones are self-sustaining. Convection around, but not in, the center produces a closed circulation aloft. Maximum convergence is between 400 and 600 mb, also the zone of steepest pressure gradients and strongest winds. Upward motion above this zone leads to condensation and deep convection, while descending motion below the convection cools the air by evaporation (see Figure 2-27).

Trade winds prevail at the surface away from the center. There is a subsidence inversion above. Trade-wind flow is disrupted at the surface closer to the center. The cyclone may or may not actually develop a low at the surface.

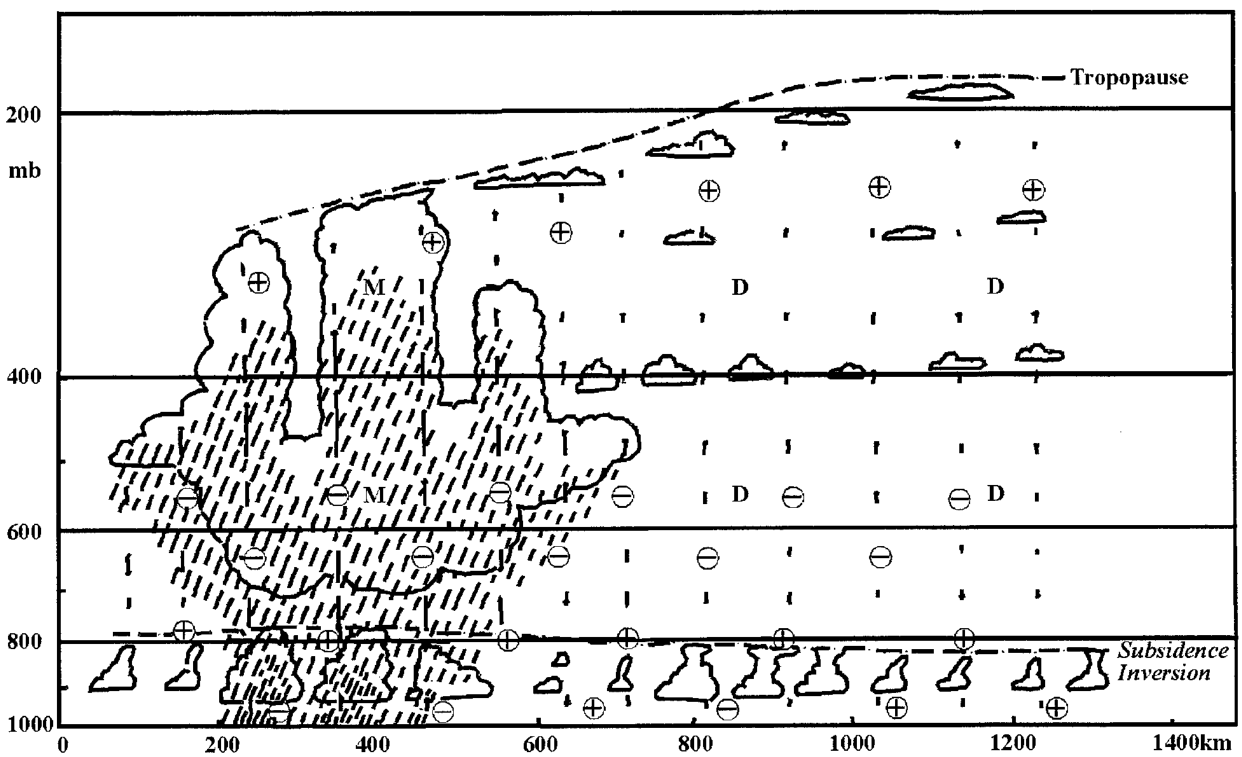


Figure 2-27. Vertical Cross-Section of a Subtropical Cyclone (from Ramage, 1971). Divergence is indicated by *plus* signs, convergence by *minus* signs. Regions of vertically moving air undergoing *dry* adiabatic temperature changes are denoted by "D"; regions undergoing *moist* adiabatic temperature changes are denoted by "M."

Tropical Cyclones. "Tropical Cyclone" is the generic southwest Indian Ocean name given to tropical storms, hurricanes, and typhoons with wind speeds above 33 knots. These storms can occur from November to April, with peaks in January and February. They are a major threat to Madagascar and Mozambique. Most develop in the monsoon trough east of Madagascar, but a few develop in the monsoon trough after crossing Madagascar. Only two tropical cyclones have hit the rest of the region in 100 years. Storms don't form in the South Atlantic. Those formed in the Arabian Sea rarely reach the Tanzanian coast. African Waves over West Africa can develop into tropical cyclones once they are out in the North Atlantic, but they have little effect on Africa. Figure 2-28 shows the average number of tropical cyclones occurring per 5-degree square per year. As shown, the highest concentration is to the east of Madagascar.

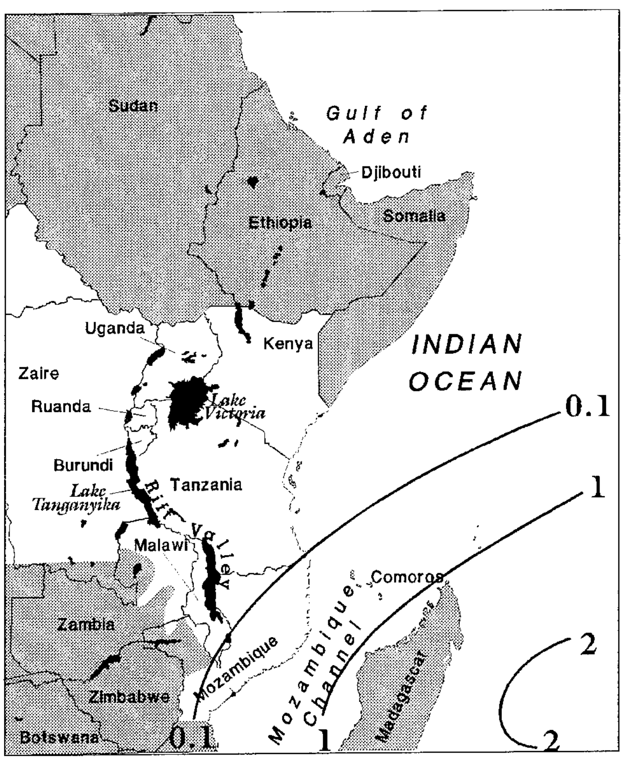


Figure 2-28. Average Number of Tropical Cyclones Per 5-Degree Square Per Year. Most tropical cyclones approach from the east and recurve southeast.

Tropical cyclones approach Madagascar from the east, usually between 10 and 20° S; the extreme northerly position is 5° S. An average of 10 storms a year form in the South Indian Ocean. Most recurve to the southeast around the South Indian Ocean High before they reach Madagascar. An average of 1 to 2 a year reach the island and/or the Mozambique Channel. Most of these also recurve to the southeast. Also possible, but rarer, are cases of dissipation over Madagascar, looping in the Mozambique Channel for several days (embedded in the monsoon trough), and moving into the African interior (ridging extends across from the South Indian Ocean High into South Africa). A 1971 cyclone remained in the channel for 10 days, producing extensive flooding over Mozambique's coast.

Cyclones moving into Africa normally produce heavy rainfall, but the winds weaken rapidly. Tropical cyclones reaching the east coast of Madagascar frequently bring winds in excess of 100 knots since they develop in the central South Indian Ocean and have plenty of time to intensify. Tropical cyclones tend to produce good weather over surrounding regions, primarily due to the upper-level outflow descending and suppressing vertical development. Zimbabwe often experiences a break in the rains and clearing when a cyclone is in the Mozambique Channel; however, the low-level northwesterly winds over Zambia move the Congo Air Boundary eastward, increasing precipitation in Malawi and eastern Zambia.

African (Tropical) Waves. African waves move from east to west at 10 to 20 knots (5 to 10 degrees of longitude a day) across Africa and into the Atlantic. Successive waves can develop every 2 to 5 days, varying from 2,200 to 4,000 km apart. The length of a wave varies from 1,500 to 4,000 km. The trough is usually tilted slightly, as shown in Figure 2-29. These waves originate over southern Chad or Sudan at the 700-mb level between 10 and 15° N from May to October. They usually remain about 100-200 km south of the NET's surface position, but in mid-summer they sometimes reach as far north as 30° N.

These disturbances usually produce little weather before late June because moisture is limited; waves seldom produce more than an increase in mid-level cloud cover. In the weaker troughs, mid-level winds are lighter than the surface winds. Convergence, cloud cover, and precipitation are on the east side of the trough.

By late July, the Mid-Tropospheric Equatorial Jet is well-established. The surface monsoon trough is near 20° N, where it brings in more moisture. More cloudiness and rainfall occur on the west side of the trough. Wind speeds of 30 to 40 knots are common in stronger waves. Closed circulations can develop at 700 mb and extend down to the surface. These systems, called "West African Cyclones," produce significant thunderstorms and precipitation. A small number can produce hurricanes when they move out into the Atlantic (see Figure 2-30, next page).

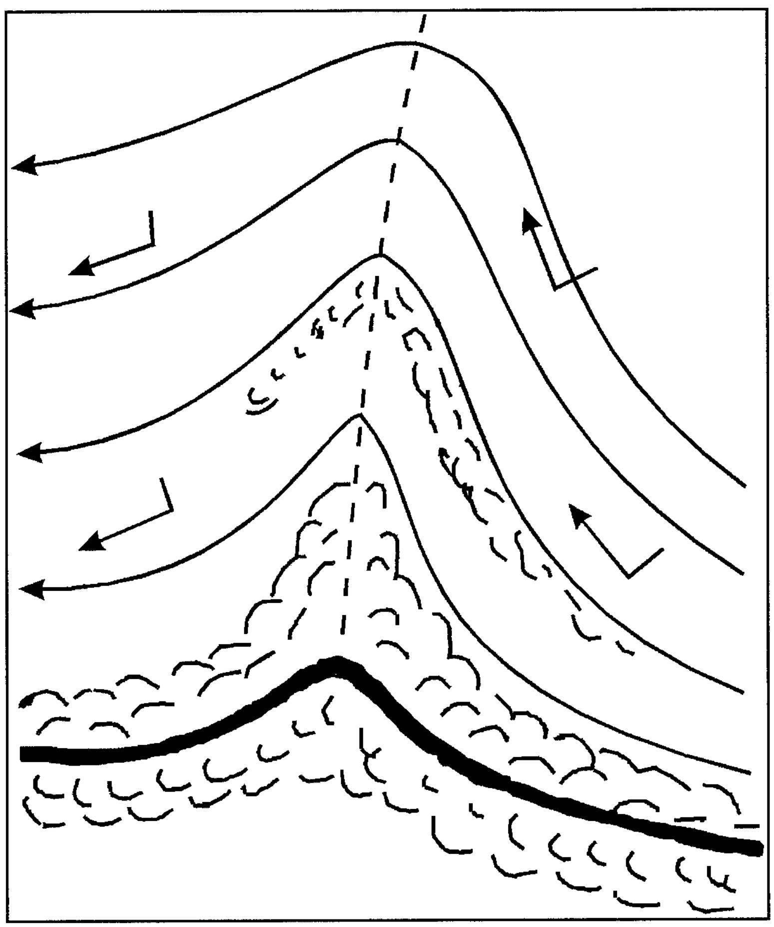
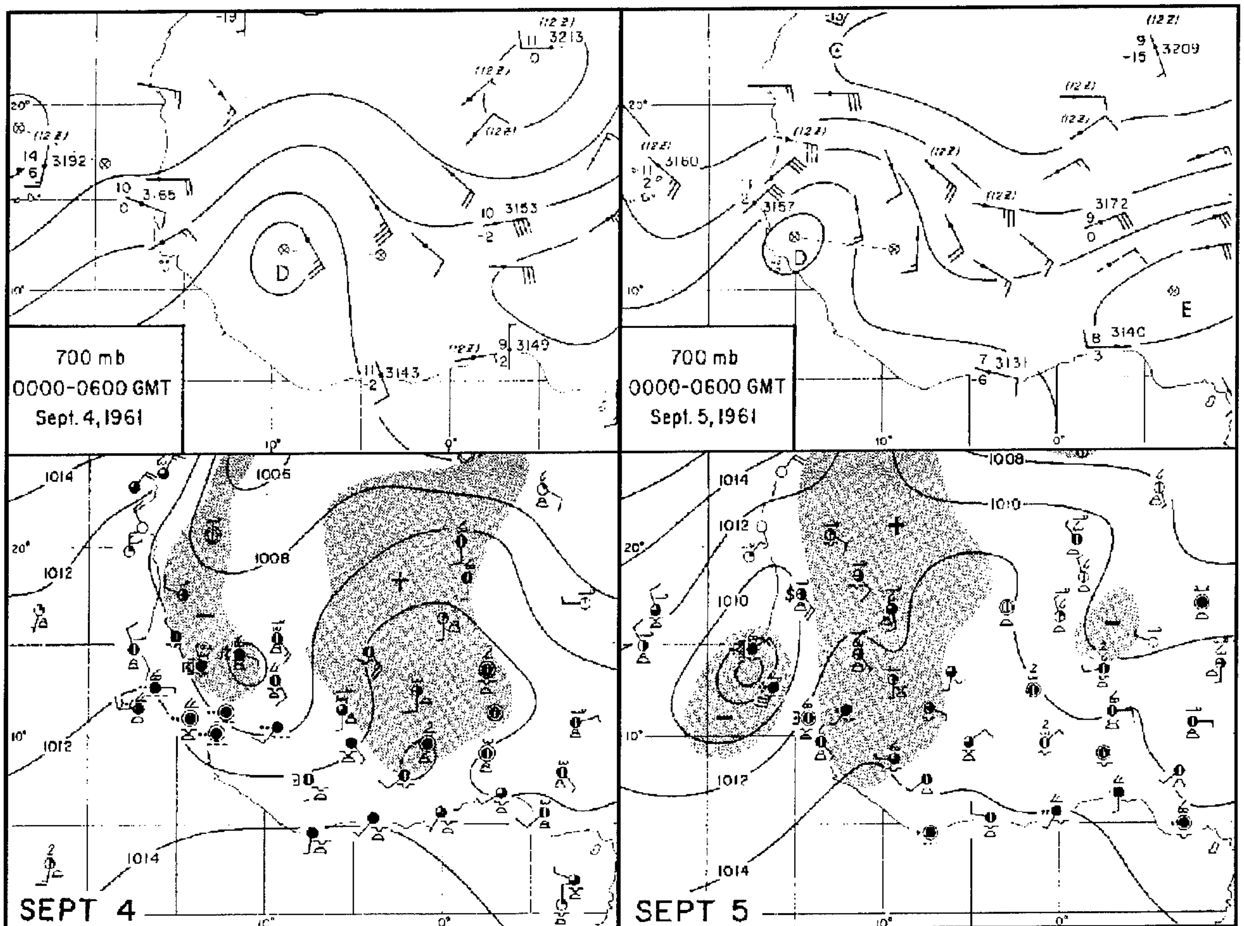


Figure 2-29. Basic Cloud and Wind Patterns of an African (Tropical) Wave (from Leroux, 1983). The trough axis is shown by the dashed line. The solid line is the 700-mb position of the NET. Wind speeds are in knots.



The D on the 700-mb chart (top) marks the center of the closed low that later became Hurricane Debbie. An African Wave is also present off the coast. The wave has a closed low at the surface.

The D on the 700 mb chart (top) marks the low that became Hurricane Debbie. It reached hurricane strength within 48 hours. The E shows another wave that became Hurricane Esther.

Figure 2-30. African Wave over West Africa, 4 and 5 September 1961, at 700 mb and Surface (from Erickson, 1963). The circled "Xs" and dashed lines on the 700-mb charts show 24-hour movement. The 24-hour pressure changes above 2 mb are shaded.

African (Tropical) Squall Lines. Although the local term for this phenomenon is "tornado," tornadoes as we know them are not associated with African squall lines, which form throughout tropical Africa but are best known over Sub-Saharan Africa between 5 and 15° N from June to September. Squall lines generally move westward at 20 to 35 knots, but they can move at up to 50 knots. They produce strong winds with gusts up to 80 knots and heavy downpours. Average duration is 12 hours. The leading edge of an African squall line is often a sharply defined, north-south arc that contains convective cells in various stages of growth. There are multiple outflow boundaries. The cirrus outflow merges into a solid shield. Three synoptic conditions necessary for African squall line development in the Sub-Sahara are listed on the next page.

• Shear and instability along the NET.

• The surface monsoon trough (which supplies large amounts of moisture) located well north (15 to 20° N).

• Convergence occurring through a deep layer of the mid-troposphere.

There are two main differences between African squall lines and mid-latitude squall lines:

• In African squall lines, the anvil cloud extends *behind* (east) of the squall line, not in front of it as in the mid-latitudes; precipitation falling from the anvil cloud enhances mesoscale subsidence.

• New convective African squall lines develop to the *west* of the outflow boundary, making the system seem to continue for several days.

To the surface observer, these systems appear as dark heavy bands of cumulonimbus with long roll clouds at the leading edges. Typical length is 300 km. They occur most frequently 250-800 km south of the NET's surface position, where the moist layer is 1,500 to 2,500 meters deep. They can occur within 24 hours of each other at the same location.The intensity of the line changes depending on synoptic and mesoscale influences. A solid deck of high-level altostratus trails the convection and usually produces light rain for up to several hours. The atmosphere behind the line is extensively mixed. The post-squall dry-bulb temperature is usually about the same as the pre-squall mid-level wet-bulb potential temperature.

Intense downdrafts and outflow boundaries can occur beneath individual convective cells. Cold downdrafts cause rapid temperature decreases and can raise large amounts of dust and sand; visibilities can be reduced to near zero. Brief and intense rainfall is common, but coverage is extremely variable. Downdraft speeds average 20 to 30 knots over flat terrain, but can be much higher, particularly near mountains. Hail is common in higher terrain. It occurs most often in eastern and central Guinea, southwestern Mali, Togo, and Benin.

African squall lines in the Sub-Sahara develop due to the presence of the Mid-Tropospheric Easterly Jet (MTEJ). This jet, at about 650 mb, is colder than the environment; it sinks progressively from east to west. When a wave develops in the flow (one source being a tropical wave), the moist southwesterly flow is forced upward. Precipitation evaporates as it falls, cooling the jet even more. If the MTEJ reaches the surface, it forms a gust front and the process becomes self-generating. The squall line generally moves to the west at the speed of the MTEJ. The zone of convection develops between the cyclonic shear side of the MTEJ and the anticyclonic shear side of the Tropical Easterly Jet (TEJ). The MTEJ is also usually stronger than the TEJ.

African squall lines often form near Lake Chad, where additional moisture is available and where easterly flow is channeled between the Tibesti and Marrah Mountains. Many squall lines develop over the Jos Plateau in central Nigeria. The high, flat terrain (around 1,000 meters) allows the MTEJ to reach the surface more easily. Some develop over the Gulf of Guinea, mainly when sea-surface temperatures are at their highest. Occurrences on the island of Bioko (previously Macias Nguema and Fernando Poo) peak in April and May. Congo Basin squall lines normally originate along the Congo Air Boundary; highest frequencies of occurrence are from November through January.

The sequence of diagrams in Figure 2-31 shows the development of an African squall line south of the surface monsoon trough and north of the equator. Shearing along the NET creates waves along the boundary. The blocking phase can be reached in the presence of an active MTEJ. The easterly flow is forced to spread to the north and south, leading to the actual thunderstorm line (a north-south arc) when the mid-level flow breaks through the NET and reaches the surface. Westerly flow is forced aloft, producing heavy rain and thunderstorms. Easterly flow drives the storms west.

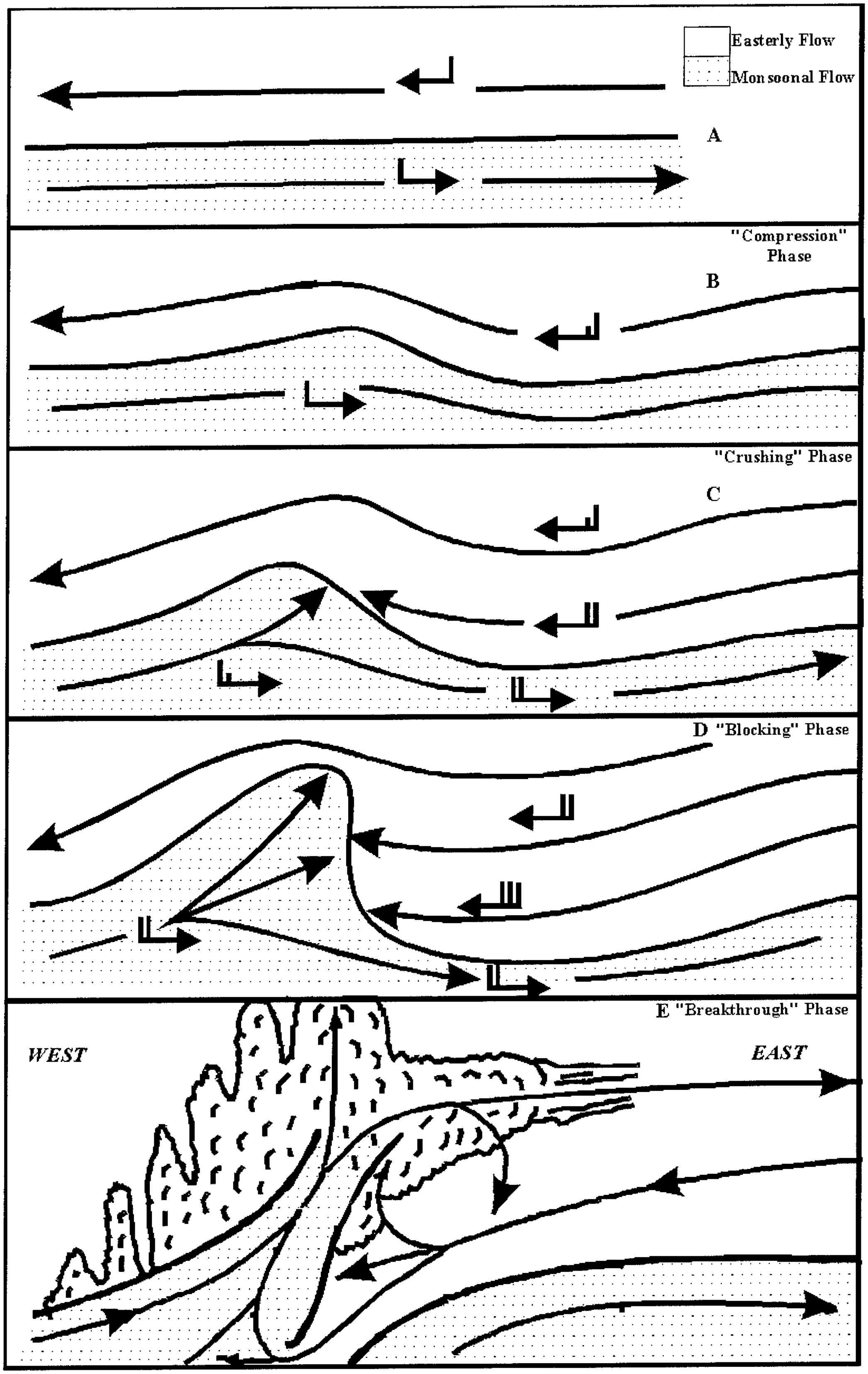


Figure 2-31. Formation of an African Squall Line (vertical cross-section). (from Hayward, 1987)

Figure 2-32 is a composite diagram of squall-line radar echoes as they moved through Korhogo, Cote d'Ivoire, in June 1981. Convection with heavy rain lasted 30 minutes at the station, followed by 30 minutes of light rain from the anvil behind the cells. Maximum surface winds were measured at 30 knots. The squall line was moving at 32 knots.

Individual thunderstorms tend to move with the low- to mid-level synoptic flow. In the Atlantic air mass north of the CAB, thunderstorms tend to move southeast toward the CAB convergence zone.

Several factors result in the dissipation of African squall lines. They have been observed to dissipate completely around coastal areas, where temperature inversions are believed to prevent the rising air from reaching the lifting condensation level (LCL). Dissipation also occurs if the supply of low-level moisture is cut off or if the MTEJ can't reach the surface. If thunderstorms have recently occurred in an area, a squall line dissipates (or only produces light rain) upon entering that area due to a lack of releasable energy. The air mass is fairly homogeneous after squall line passage; subsidence can be present. Some squall lines regenerate after passing such an area.

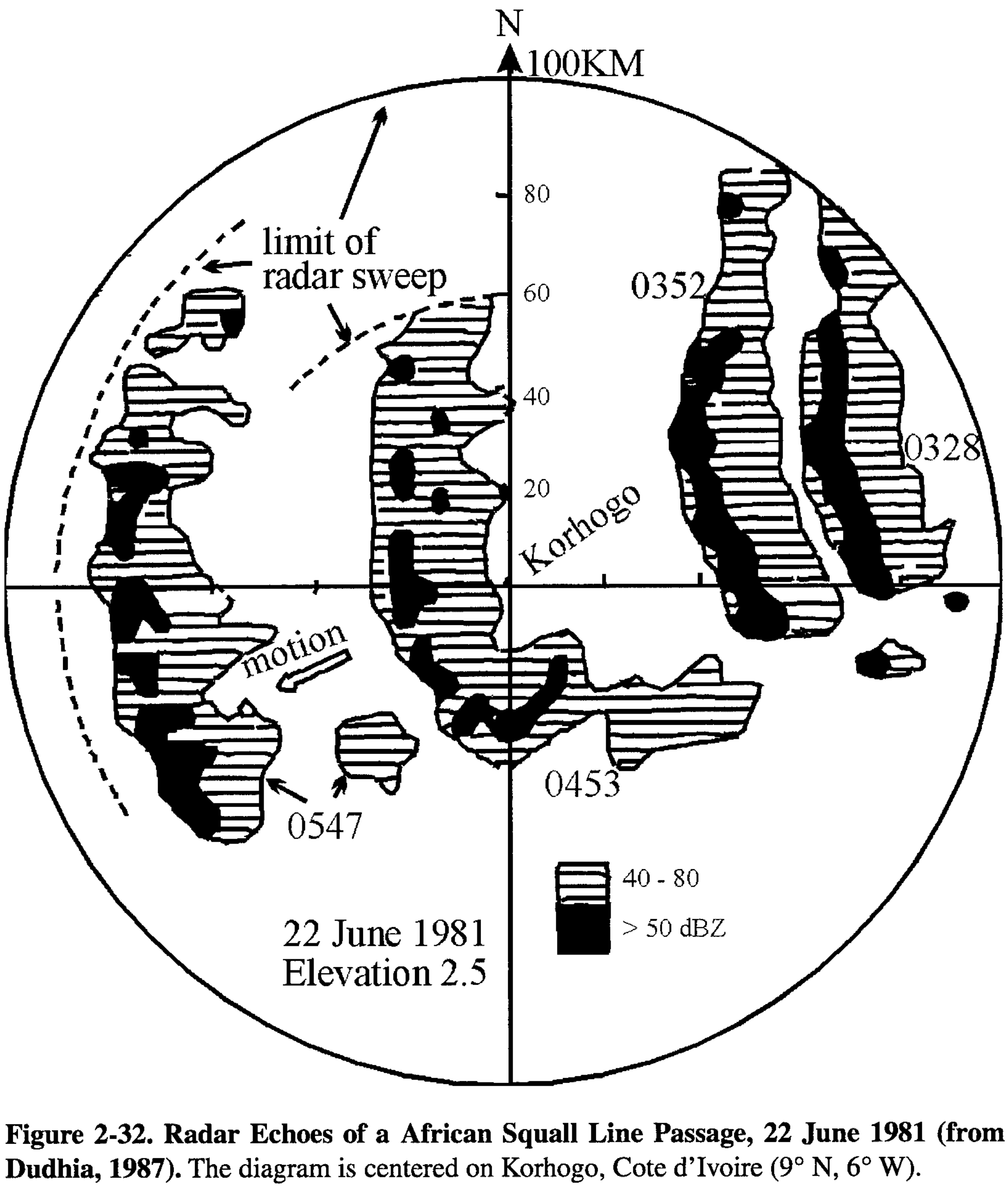


Figure 2-32. Radar Echoes of a African Squall Line Passage, 22 June 1981 (from Dudhia, 1987). The diagram is centered on Korhogo, Cote d'Ivoire (9° N, 6° W).

Turkana Channel Jet. This mesoscale, low-level jet is present the year-round over northwestern Kenya, situated in a narrow channel between the Ethiopian and Kenyan Highlands. It has been observed at Marsabit, Kenya (2° N, 38° E) and it continues over Lake Turkana. Winds are normally southeasterly in the jet core at 450 to 600 meters AGL. The top of the jet is usually below 900 meters. Winds back with height.

The Turkana Channel Jet advects moisture from the Indian Ocean far inland, where the moisture results in cloudiness normally associated with a sea breeze front, but no rainfall.

General flow into the channel is produced by a strong pressure gradient, with higher pressure to the east and lower pressure to the west. During the summer, a branch of the Somali Jet enters the channel. During the winter, Northeast Monsoon flow enters the narrow channel, where terrain funnels the flow and produces the jet.

Maximum mean wind speeds exceed 50 knots during February and March. Winds are generally stronger in the morning than in the afternoon, when speeds are weakened by vertical mixing. In the morning, winds exceed 60 knots 15% of the time and 100 knots 5% of the time. Record speeds above 150 knots have been recorded during pilot balloon observations.

Land/Sea Breezes. Differential surface heating generates this diurnal phenomenon along most of Africa's coastline. The marine boundary layer rarely extends above 915 meters AGL or 30 km inland unless modified by synoptic flow. There are two types of land/sea breezes: "common" and "frontal."

- ***"Common" land/sea breezes*** affect all coastal areas of Equatorial Africa. Figure 2-33 illustrates the "common" land/sea breeze circulation under calm conditions with no topographic influences and a uniform coastline. Onshore (A) and offshore (B) flow intensifies in proportion to daily heat exchanges between land and water. Common land/sea breezes normally reverse at dawn and dusk.

- ***"Frontal" land/sea breezes*** are sharp discontinuities between land and sea air masses. Strong offshore gradient flow produces the frontal land breeze. It delays the onset of the sea breeze by 1 to 4 hours as gradient flow prevents the sea breeze boundary layer (or "front") from moving ashore. When it does move onshore, it sometimes sustains 20-knot winds for 15-45 minutes. Figure 2-34 shows a typical frontal sea breeze.

High terrain near the coastline modifies the land/sea breeze in several ways. Orographic lifting produces sea breeze-stratiform/cumuliform cloudiness and deflects surface winds, while the mesoscale mountain circulation accelerates the land breeze over water. Elevated coastal topography produces steep nighttime temperature gradients.

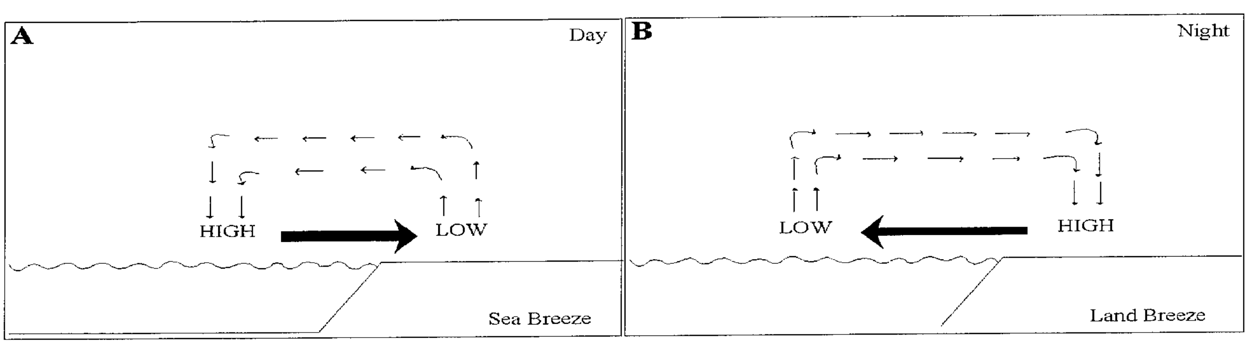


Figure 2-33. The "Common" Sea (A) and Land (B) Breezes. Thick arrows depict the gradient flow.

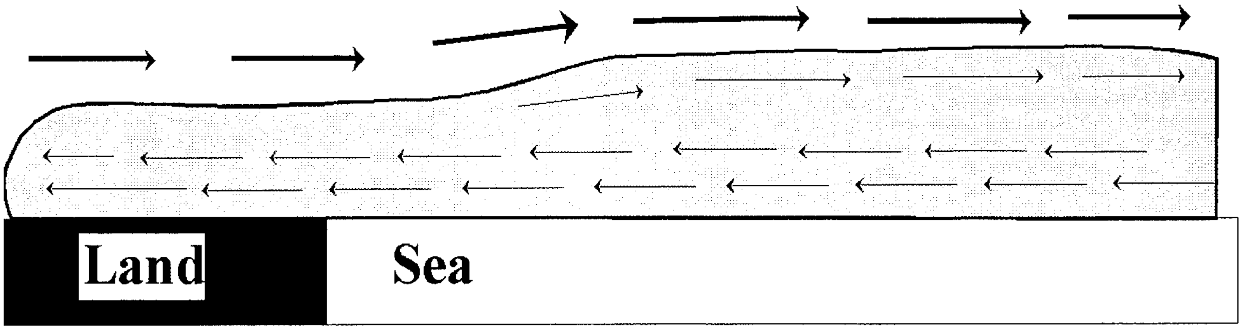


Figure 2-34. A Fully Formed "Frontal" Sea Breeze. Arrows depict wind flow; the shaded area is the marine air mass.

Figure 2-35 shows the land/sea breeze circulation with onshore gradient winds and coastal mountains. Onshore gradient flow accelerates orographic lifting by day, and produces localized convergence over open water in the early morning.

Along the North Atlantic and Gulf of Guinea coasts, the sea breeze is present year-round, but it is most common along the coasts of Mauritania, Senegal, and Togo. The sea breeze is strongest from June to August, averaging 10-15 knots as it augments the

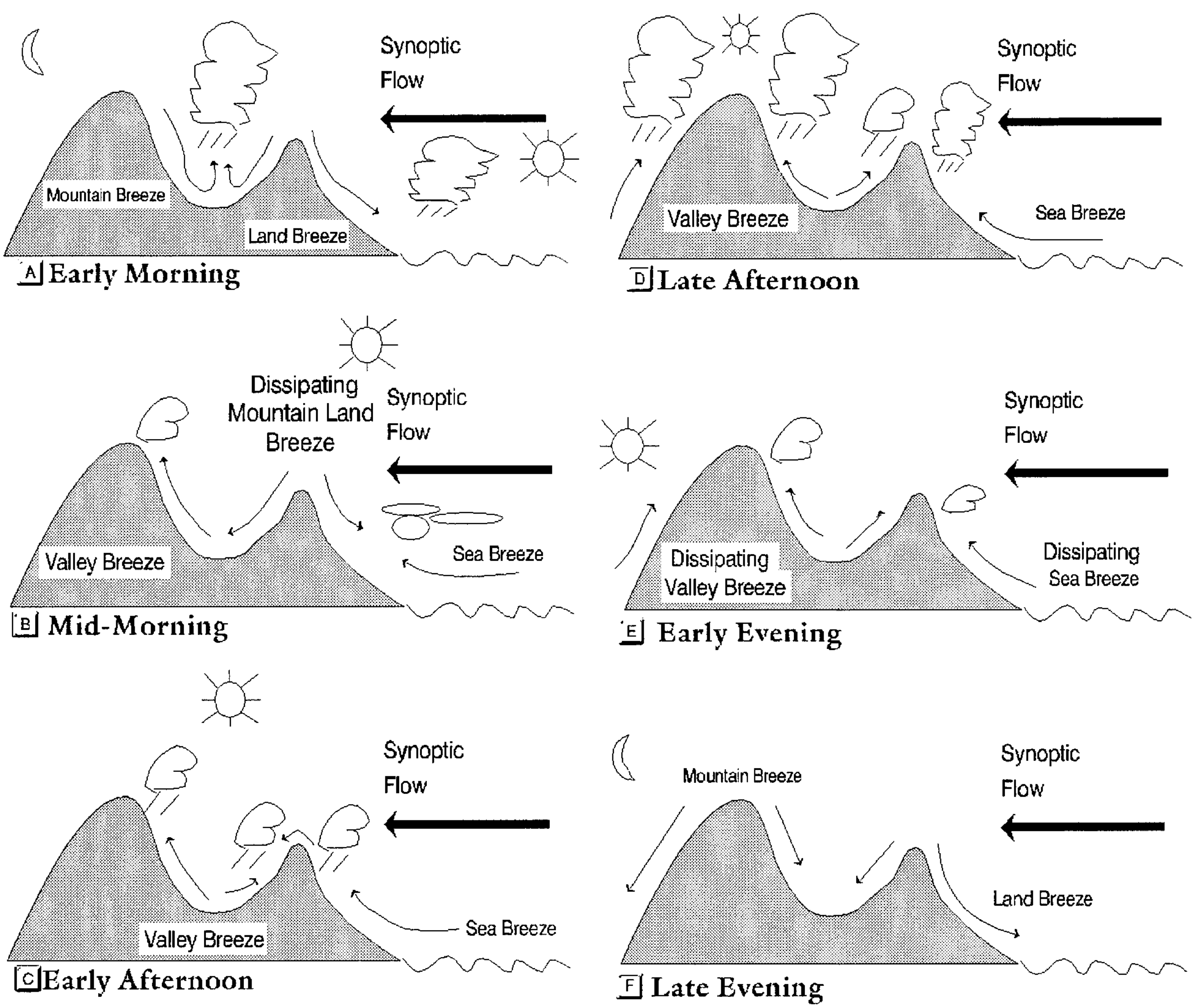


Figure 2-35. Land/Sea Breeze with Onshore Gradient Flow.

southwesterly flow. It is usually 1,200 meters deep and strongest where the coast is backed by hills. During the dry season, the cloud lines produced by the sea breeze are visible daily from Liberia to Nigeria. The land breeze is usually restricted to coastal margins and is only about 90 meters deep. It is strongest in January (when it averages 5 knots) and weakest in July.

On the eastern coast of Africa, land/sea breezes can be present the year-round, except when overridden by stronger winds from disturbances such as tropical cyclones or polar surges. The sea breeze is strongest in the summer with speeds of between 10 and 25 knots. Land breezes are generally westerly and sea breezes east-northeasterly.

Coastal configuration also has an effect on land/sea breezes. Coastlines perpendicular to landward synoptic flow maximize sea breeze penetration, while coastlines parallel to the flow minimize them.

Land/Lake Breezes. Several localized variations of the land/sea breeze circulation are caused by differential heating over large lakes. This circulation occurs in the absence of strong synoptic flow; it has a vertical depth ranging from 200 to 500 meters (650 to 1,650 feet) AGL. Figure 2-36 shows a land/lake circulation and cloud pattern with no synoptic flow. In late afternoon, a cloud-free lake is surrounded by a ring of convection some 20 to 40 km inland from shore. By early morning, the flow reverses and localized convergence occurs over open water.

Convection near the lakes of the Rift Valley is modified by synoptic flow and mountains. Daytime convection normally forms first over the mountains and is then advected over the lakes. Lake Victoria's convection patterns are particularly important to the weather of the surrounding countries. The Southeast and Northeast Monsoons control Lake Victoria's synoptic flow; maximum precipitation zones around the lake shift northward and southward with the season. The largest amounts occur in April and November when the NET moves through.

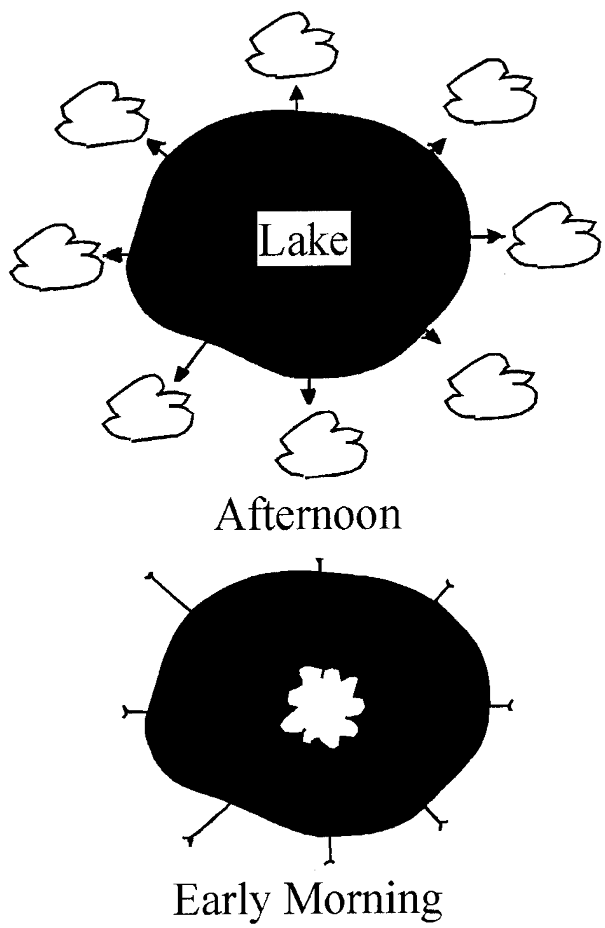


Figure 2-36. Idealized Land/Lake Breezes with Cloud Pattern.

Figure 2-37 shows typical morning and afternoon surface flow over Lake Victoria in April. The dashed line in the afternoon panel marks the sea-breeze convergence zone. Speed convergence with the land breeze occurs west of the lake. Synoptic flow is dominated by the Southeast Monsoon. High terrain to the east of the lake enhances convection there. From an inland afternoon maximum, convection gradually moves westward with the easterly synoptic flow as the sea breeze weakens and the land breeze develops. On the east coasts, highest convection frequencies are from 1800 to 0400L, with a peak at 2300L. In the center of the lake, highest convection frequencies are from 0400 to 0800L. On the west coast, the highest frequencies are from 0300 to 1400L, with a peak at 0800L.

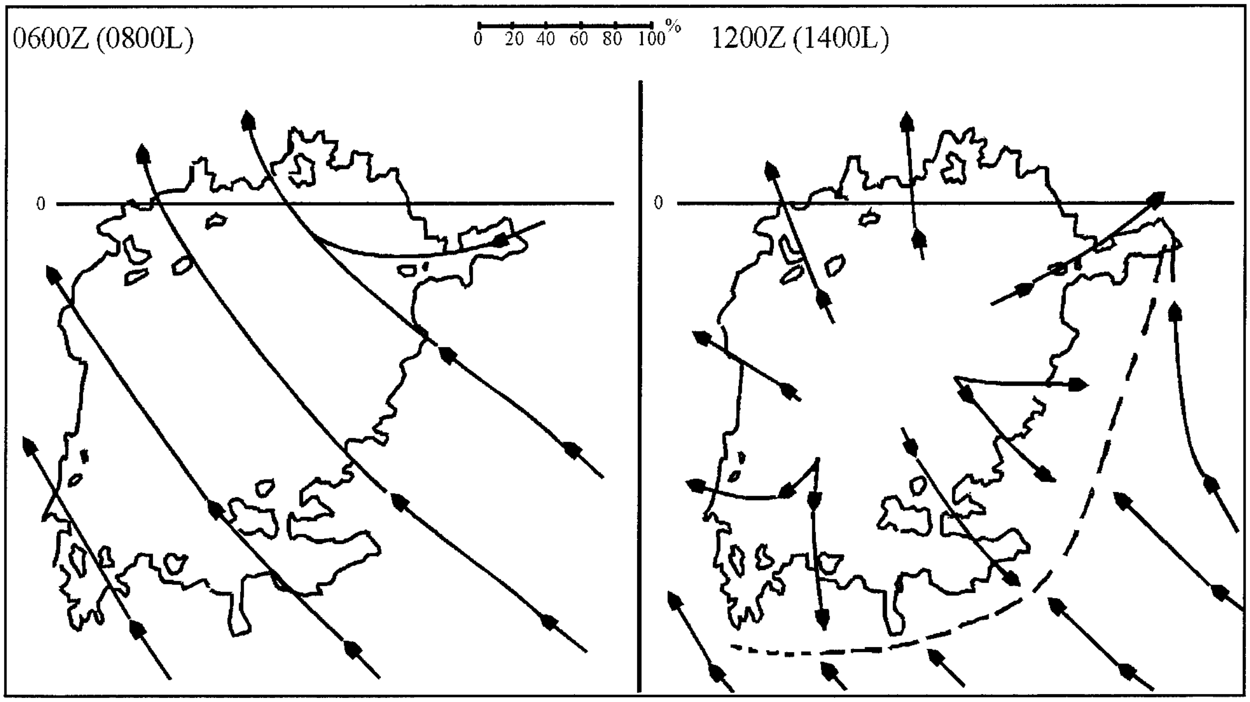


Figure 2-37. April Surface Streamlines in the Morning (left) and Afternoon (right) Over Lake Victoria (from Leroux, 1983).

Lake Victoria's lake breeze is about 3,000 meters deep; it can penetrate 55 km inland. It reaches its maximum at 1500L with average speeds from 10 to 15 knots. The land breeze reaches its maximum between 0600 and 0900L with average speeds from 4 to 8 knots. In some locations, thunderstorms develop on 2 out of every 3 days. At some stations in the Kenya Highlands east of the lake, hail falls on more than 100 days a year.

A quasi-permanent trough, referred to as the "Lake Victoria Surface Trough," extends southward over Lake Victoria from the Sudanese Low/Trough. A cyclonic center can form over the lake from May to September. A mid-level high (called the "Nairobi Anticyclone") develops over the lake at approximately 4,200 meters. These features help produce the violent thunderstorms in the area.

Mountain-Valley and Slope Winds develop under fair skies with light and variable synoptic flow. The two types of terrain-induced winds are shown in Figure 2-38. Mountain-valley winds tend to be stronger than slope winds and can override their influence.

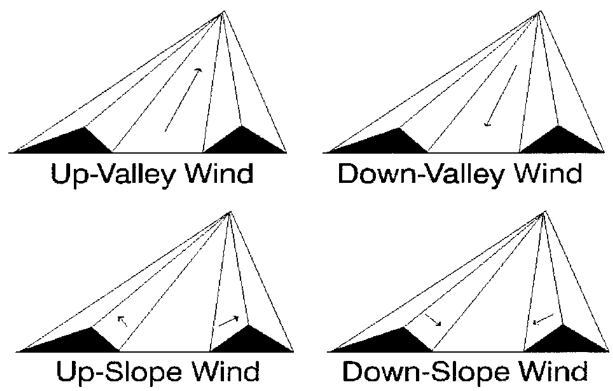


Figure 2-38. Mountain-Valley and Slope Winds (from Whiteman, 1990).

Mountain-Valley winds are produced in response to a pressure gradient between a mountain valley and a plain outside the valley. Air within the valley heats and cools faster than air over the plain. Daytime up-valley winds are strongest, averaging 10-15 knots between 200 and 400 meters AGL. Nighttime down-valley winds average only 3-7 knots at the same level. Peak winds occur at the valley exit. Deep valleys develop more nocturnal cloud cover than shallow valleys because nocturnal airflow convergence is stronger. The mesoscale mountain-valley circulation, which has a maximum

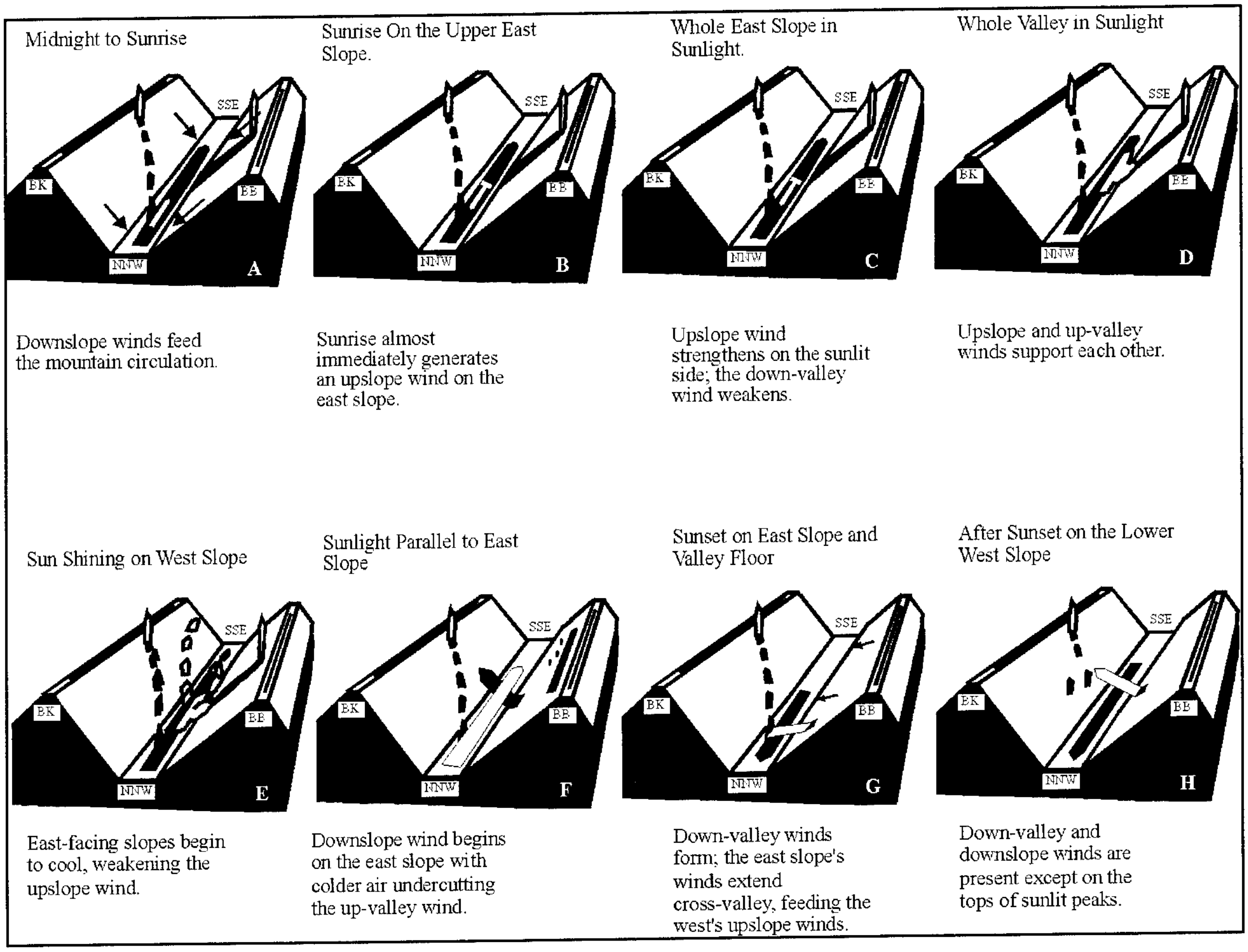


Figure 2-39. Diurnal Variation of Slope and Mountain-Valley Winds (from Barry, 1981).

vertical extent of 2,000 meters, is determined by valley depth and width, prevailing wind strength in the mid-troposphere (stronger winds producing a shallower circulation), and the breadth of microscale slope winds. The return flow aloft is much weaker and broader since it isn't confined to a narrow valley.

Slope Winds develop along the surface boundary layer (0-150 meters AGL) of mountains and large hills. Mean daytime up-slope wind speeds are 6-8 knots; mean nighttime down-slope wind speeds are 4-6 knots. Steep slopes can produce higher speeds, but these speeds are found at elevations no higher than 40 meters AGL. Down-slope winds are strongest during the season with the greatest cooling, while up-slope winds are strongest during the season of greatest heating. Up-slope winds are strongest on the slope facing the sun. Winds from a larger mountain can disrupt the winds of a smaller mountain. In some locations, cold air can be dammed up on a plateau or in a narrow valley. When sufficient air accumulates, it can spill over in an "air avalanche" of strong winds.

Figure 2-39 shows the life cycle of a typical mountain-valley and slope-wind circulation. Both valley and slope winds are shown in relation to two ridges (BK and BB) oriented NNW-SSE. The dark arrows show the flow near the ground; the light arrows show movement of the air above the ground. Mountain inversions develop when cold air builds up along wide valley floors. Cold air descends from slopes above the valley at 8-12 knots, but loses momentum when it spreads out over the valley floor. Wind speeds average only 2-4 knots by the time the down-slope flow from both slopes converge. The cold air replaces warm, moist valley air at the surface and produces a thin smoke and fog layer near the base of the inversion. First light initiates up-slope winds by warming the cold air trapped on the valley floor. Warming of the entire boundary layer begins near the 150-meter level AGL.

Mountain Waves develop when air at lower levels is forced up over the windward side of the ridge. Criteria for mountain wave formation include sustained winds of 15-25 knots, winds increasing with height, and flow oriented within 30 degrees of perpendicular to the ridge.

Wavelength amplitude is dependent on wind speed and lapse rate above the ridge. Light winds follow the contour of the ridge with little displacement above and rapid damping beyond. Stronger winds displace air above the stable inversion layer; upward displacement of air can reach the tropopause. Downstream, the wave propagates for an average distance of 50 times the ridge height. Rotor clouds form when there is a core of strong wind moving over the ridge, but the elevation of the core does not exceed 1.5 times the ridge height. Rotor clouds produce the strongest turbulence. The clouds may not always be visible in dry regions. Figure 2-40 is an illustration of a fully developed lee-wave system.

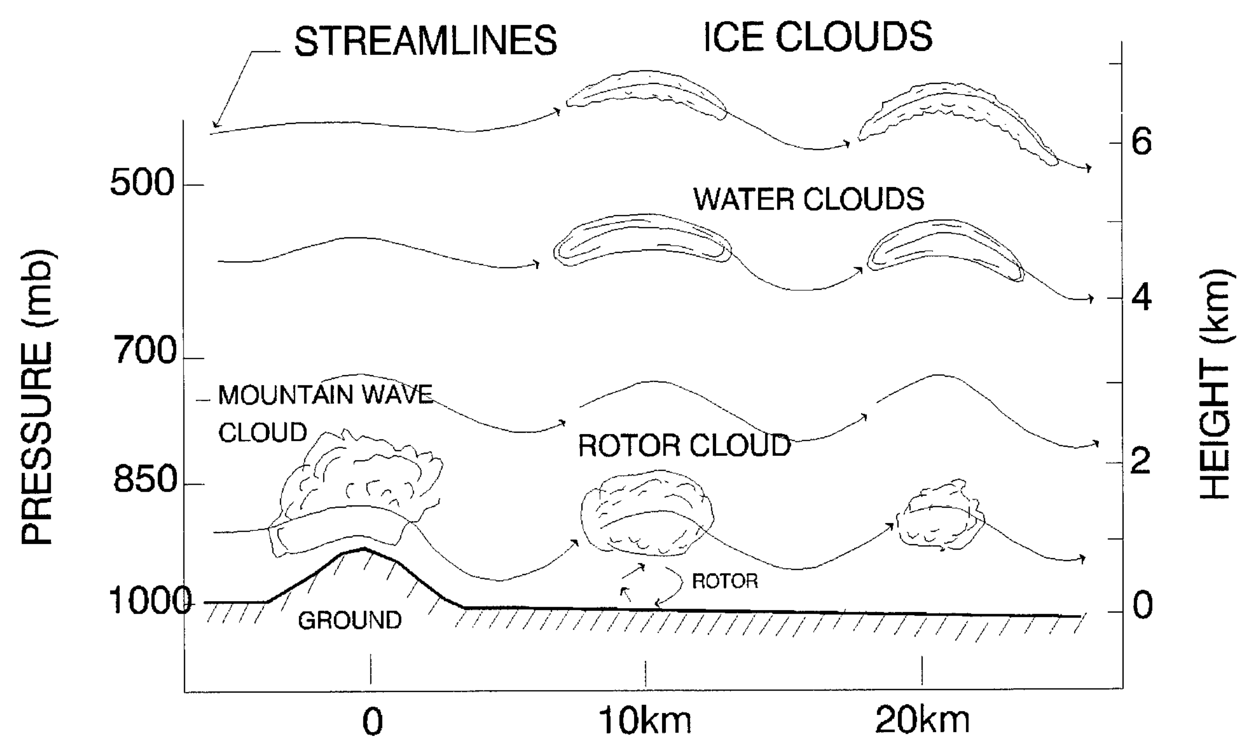


Figure 2-40. Fully Developed Lee-Wave System (from Wallace and Hobbs, 1977).

Duststorms/Sandstorms. Given the right conditions, duststorms are dominant features in and near the deserts of the region. Duststorms carry suspended particles over long distances, often reducing visibility to less than 10 meters. Season of occurrence, wind direction, amount of particulate matter, and duration vary by locality. Large-scale duststorms often persist for 1 or 2 days before a frontal passage (such as an Atlas Low), or with a synoptic-scale squall line. Mesoscale squall lines may reduce visibility to less than 1,000 meters for several minutes to an hour. Sandstorms differ from duststorms only in the size of the suspended particles. Sand, being heavier, is seldom raised to more than 1-2 meters above the ground; the particles settle quickly.

Strong pressure gradients produced by mid-latitude surges and by tropical disturbances generate the winds needed to produce synoptic-scale duststorms. Most large-scale dust clouds move towards the west and the equator. Those in the Sahara are elongated plumes, typically 1,000 km long and 200 km wide.

Winds of 15-20 knots are sufficient to lift dust and sand. The mean threshold value is 17 knots, but speeds as low as 10-12 knots can produce duststorms. A pressure gradient of 6 mb/10 degrees of latitude produces widespread duststorms 50% of the time. Only a 4 mb/10 degrees of latitude surface pressure gradient is necessary to generate dust-laden surface winds.

Dust devils resemble miniature tornadoes, but their wind speeds are generally between 10 and 25 knots. They can, however, get strong enough to flatten huts. They form in clear skies and are set off by intense summer daytime heating and local turbulence. Diameters range from 3 to 90 meters, averaging around 6 meters. Most reach 75 meters high, but dust has been observed at 900 meters. Dust devils move at about 10 knots and last for 1 to 5 minutes. Visibilities are near zero in the vortex. They are common across the desert regions of the southern African interior.

The origin and nature of duststorms depend upon (1) general synoptic conditions, (2) local surface conditions, (3) seasonal considerations, and (4) diurnal considerations.

(1) General Synoptic Conditions.

• *Active cold fronts.* Duststorms can develop with frontal passages. Strong fronts increase the size of the area affected considerably and can produce a "wall of sand."

• *Convective activity.* Convective downdrafts commonly reach speeds needed to produce duststorms and sandstorms. Visibilities can be greatly reduced within minutes. Duststorms created by convective downdrafts are frequently called "Haboobs."

• *Stagnant Surface High Pressure.* The Saharan High normally strengthens over the subtropics during extended fair-weather periods. This high sometimes produces severe and widespread duststorm activity that is most difficult to forecast. Although such situations are easy to recognize, precise locations (timing/areal extent) are difficult to infer with so little data available. Stagnant air aloft provides little ventilation to remove the dust.

(2) Local Surface Conditions. Soil type and condition control the amount of particulate matter that can be raised into the atmosphere. Dry sand or silt, for example, is easily lifted by 10-15 knot winds. Haze is a persistent feature of the sandy deserts. The fine dust, salt, or silt can be suspended for weeks and travel hundreds, even thousands, of kilometers from the source. Vehicles crossing the sand break through the crust easily; even light winds can raise dust. A "Harmattan" (see next section) blows dust from the Sahara southward and out into the Atlantic. On rare occasions, these particles precipitate back to the surface as "mud rain." Figure 2-41 shows the primary Sahara dust trajectories across western Africa.

(3) Seasonal Considerations.

• *Winter.* Large areas of dust/haze develop when there is subsidence aloft and a lack of turbulent mixing. Most duststorms develop along frontal boundaries. Synoptic-scale winds of only 10-15 knots can lower visibility to below 5,000 meters over large areas for up to 12 hours.

• *Summer.* Convection produces most duststorms, but late-spring frontal systems also produce them. Duststorms are more frequent than in the winter. Local visibilities are below 5,000 meters in areas where the soil is dry.

(4) Diurnal Considerations.

• *Daytime.* The lowest visibilities occur around 0900L, shortly after the inversion breaks and turbulent surface mixing raises the dust. Distant tree tops can be visible at this time, but their bases are obscured by the dust/haze. Daytime heating produces turbulent mixing in the lowest layers. Hot, dry winds transport dust aloft to the base of the large-scale subsidence inversion. Persistent dryness allows dust to reach 3,000 meters MSL, where it can remain suspended for days or weeks.

• *Nighttime.* Cooler surface temperatures create stable conditions in the surface layer. Turbulent mixing is minimized; visibilities improve during the night and are best between 2000 and 0600L as the temperature inversion produces light surface winds. Dust settles beneath the inversion layer throughout the night; visibilities improve to 6-10 km.

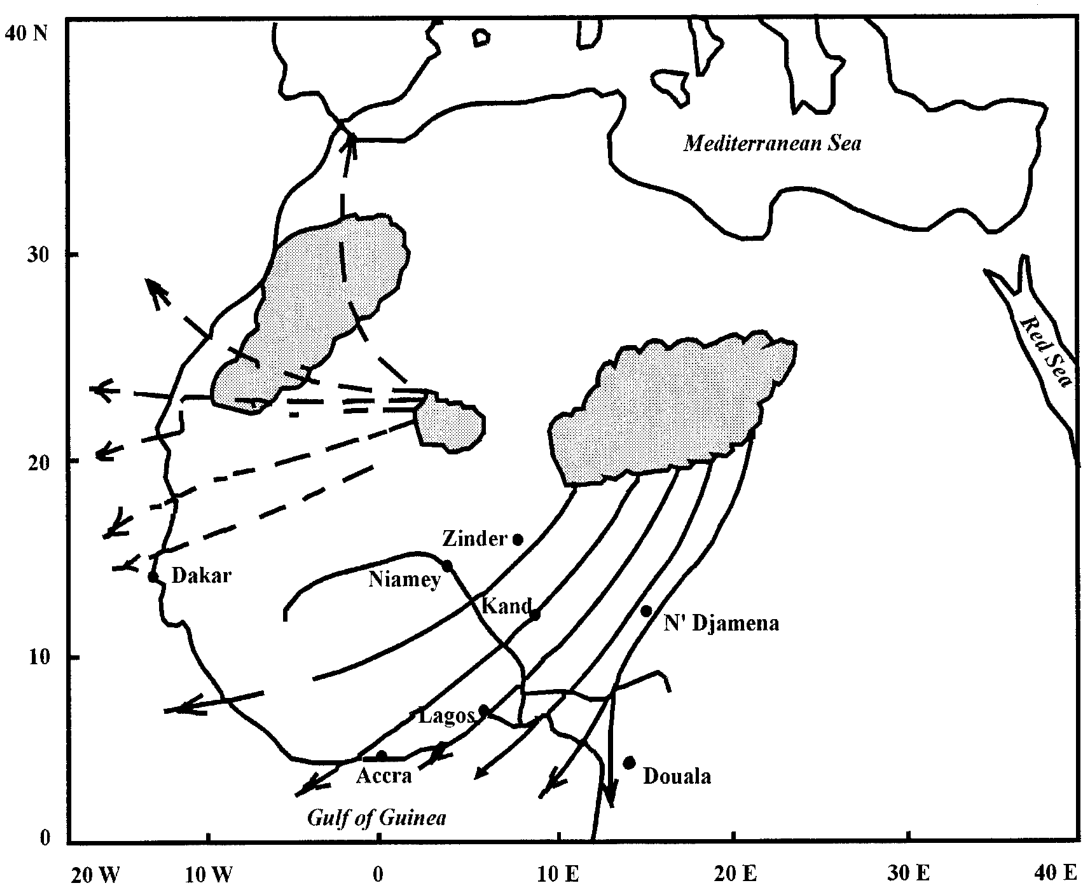


Figure 2-41. Saharan Dust Trajectories Across Western Africa (from Omotosho, 1989). The main sources of dust are shaded.

The Harmattan. This dry, dust-bearing northeasterly-to-easterly wind originates in the Sahara as outflow from the Saharan and Azores Highs during the winter. Severe Harmattans occur behind strong cold fronts with Atlas Lows; winds reach 30-45 knots. Three to five severe Harmattans normally occur from January to May. Harmattans result when turbulent surface mixing produces thick dust haze that normally reaches 300 meters AGL, but can reach 3,000-3,600 meters MSL and extend southward to 5° N. Visibility is generally less than 6,000 meters, but values as low as 200 meters have been reported. Severe duststorms, extremely low visibility, and high winds can persist for 12 to 24 hours. Figure 2-42 shows a Harmattan occurring over North Africa in March 1991.

Harmattan haze is suspended dust associated with fair weather. It can be present the year-round and can persist for extended periods. Harmattan haze results when dry, dust-laden air from the Sahara reaches the NET and is forced aloft. Although horizontal visibilities increase south of the monsoon trough as the dust layer is forced into the atmosphere, slant-range visibilities are worse. Horizontal visibilities are usually 5-10 km; slant range, only 2-5 km.

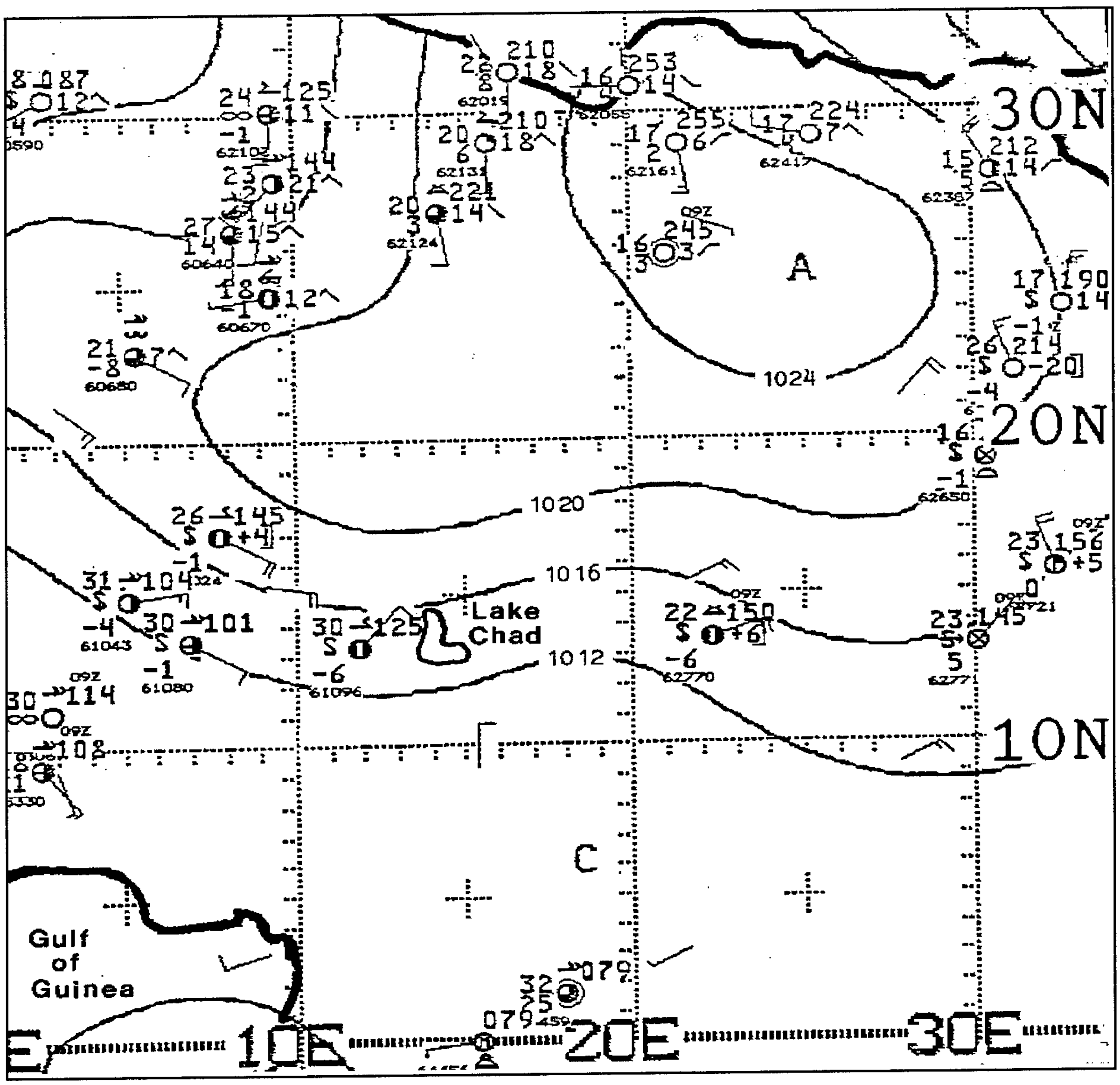


Figure 2-42. Surface Chart Showing Harmattan-Produced Duststorm over North Africa, 6 March 1991. Wind barbs without station data are satellite-derived.

Guti and Chiperoni. The "Guti" of Zimbabwe and Zambia and the "Chiperoni" of Malawi are local Africa into the Mozambique Channel. As this cool and moist air moves inland into the Limpopo, Zambezi, and Shire River valleys, it rises along the highlands and reaches southeastern Zimbabwe and southern Malawi as a cold, nearly saturated air mass. Adjoining districts of Zambia are also affected, though less often.

Invasions of the Guti and Chiperoni are normally associated with moderate-to-strong southeasterly winds that can gust up to 45 knots. Widespread stratus with bases between 500 and 1,000 feet sometimes extends as far west as Bulawayo in Zimbabwe and the Muchinga Escarpment in Zambia (800 kilometers inland). Precipitation is generally even at night.

During the rainy season, these disturbances are often preceded by squall-line thunderstorms that develop 150 kilometers ahead of the boundary of moist, southeasterly flow. The stratus is usually thicker and more persistent than in the dry season. During the dry season, the tops of the stratus are generally lower; the Guti/Chiperoni tends to begin in the morning with lifting or a complete clearing by afternoon.

Wet-Bulb Globe Temperature (WBGT) Heat-Stress Index. The WBGT heat-stress index provides values that can be used to calculate the effects of heat stress on individuals. WBGT is computed using the formula:

$$WBGT = 0.7WB + 0.2BG + 0.1DB,$$

where: WB = wet-bulb temperature
BG = Vernon black-globe temperature
DB = dry-bulb temperature

A complete description of the WBGT heat-stress index and the apparatus used to derive it is given in Appendix A of TB MED 507, *Prevention, Treatment and Control of Heat Injury, July 1980, published by the Army, Navy, and Air Force.* The physical activity guidelines shown in Figure 2-43 are based on those used by the three services. Note that the wear of body armor or NBC gear adds 6° C to the WBGT; activity should be adjusted accordingly.

WBGT (° C)	Water Requirement	Work/rest Interval	Activity Restrictions
32-up	2 quarts/hour	20/40	Suspend all strenuous exercise.
31-32	1.5-2 quarts/hour	30/30	No heavy exercise for troops with less than 12 weeks hot weather training.
29-31	1-1.5 quarts/hour	45/15	No heavy exercise for unacclimated troops, no classes in sun, continuous moderate training 3rd week.
28-29	.5-1 quart/hour	50/10	Use discretion in planning heavy exercize for unacclimated personnel.
24-28	.5 quart/hour	50/10	Caution: Extremely intense exertion may cause heat injury.

Figure 2-43. WBGT Heat-Stress Index Activity Guidelines.

Figure 2-44 gives mean daily high WBGTs for January, April, July, and October. For more information, see USAFETAC/TN–90/005, *Wet Bulb Globe Temperature, A Global Climatology*.

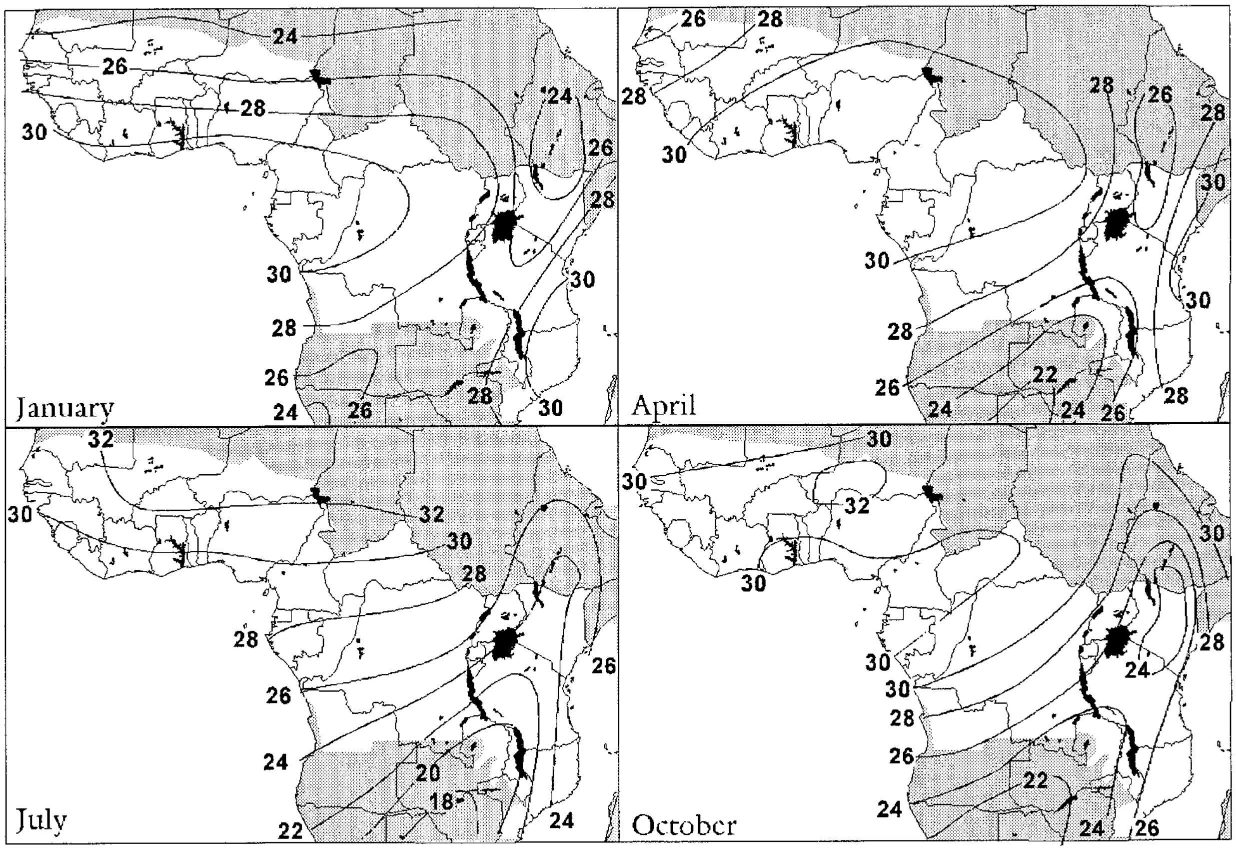
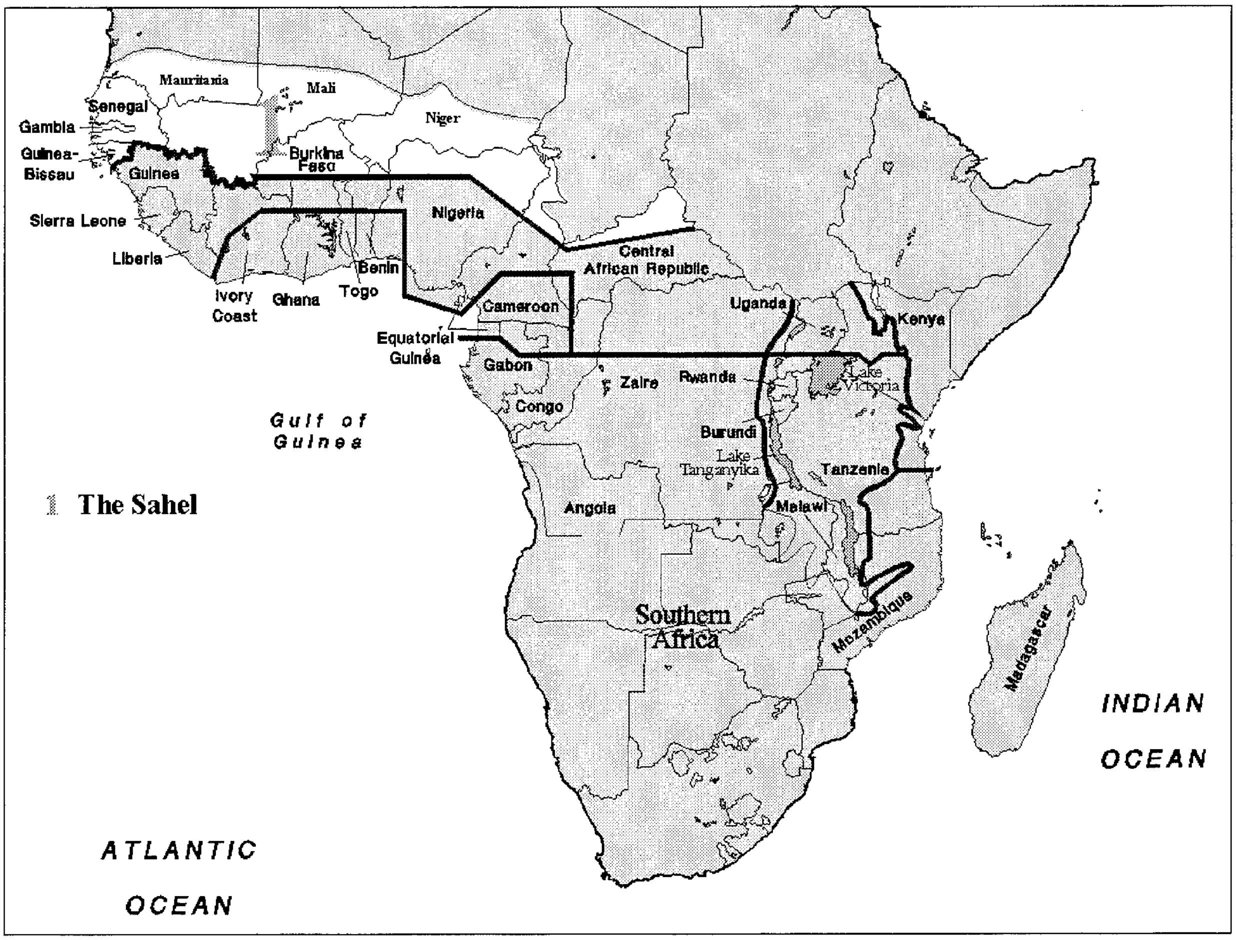


Figure 2-44. Average Daily High WBGT (° C).

Chapter 3

THE SAHEL

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) of the Sahel, a semiarid zone between the Sahara Desert and tropical West Africa that comprises Senegal, Gambia, Guinea-Bissau, the southern parts of Mauritania, Mali, and Niger, and the northern parts of Burkina Faso, Benin, Nigeria, Cameroon, and the Central African Republic.



SAHEL GEOGRAPHY

Seasons. There are two seasons in this semiarid transition zone between the Sahara Desert to the north and the moister climate of the Gulf of Guinea to the south. The wet season runs from May to October and the dry season runs from November to April.

Boundaries. The northern border of the Sahel is defined by the line at which annual rainfall exceeds 250 mm. The southern boundary is a line that marks the southernmost point of the July-September wet season and a November-April dry season. Geographically, the climatic zone known as the Sahel lies between 7° and 18° N and from 17° W to 24° E. The Sahel is bounded on the north by the Sahara, on the west by the Atlantic Ocean, on the east by Sudan's border with Chad, and on the south by a line from the northern border of Guinea through the northern portions of Nigeria, Cameroon, and the Central African Republic.

Major Terrain Features. A narrow coastal band extends inland about 15 to 50 kilometers from the Atlantic Ocean. Marshes, estuaries, and mangrove swamps are prevalent along the coast, especially south of Cape Verde, the westernmost point on the African continent. North of Cape Verde, the coast becomes increasingly arid, with sand dunes stretching down to the ocean. The entire coastline is subject to heavy surf, especially during the July-September wet season. Most of the rest of the Sahel is characterized by monotonous rolling plains with elevations mostly around 400 meters. In the western Sahel, terrain rises gradually from the Atlantic coast of Senegal toward the Fouta Djallon Massif in southeast Senegal, where elevations reach 1,500 meters. Farther east, the plains of the Sahel again give way to higher terrain; the Jos Plateau rises to nearly 1,800 meters in northern Nigeria.

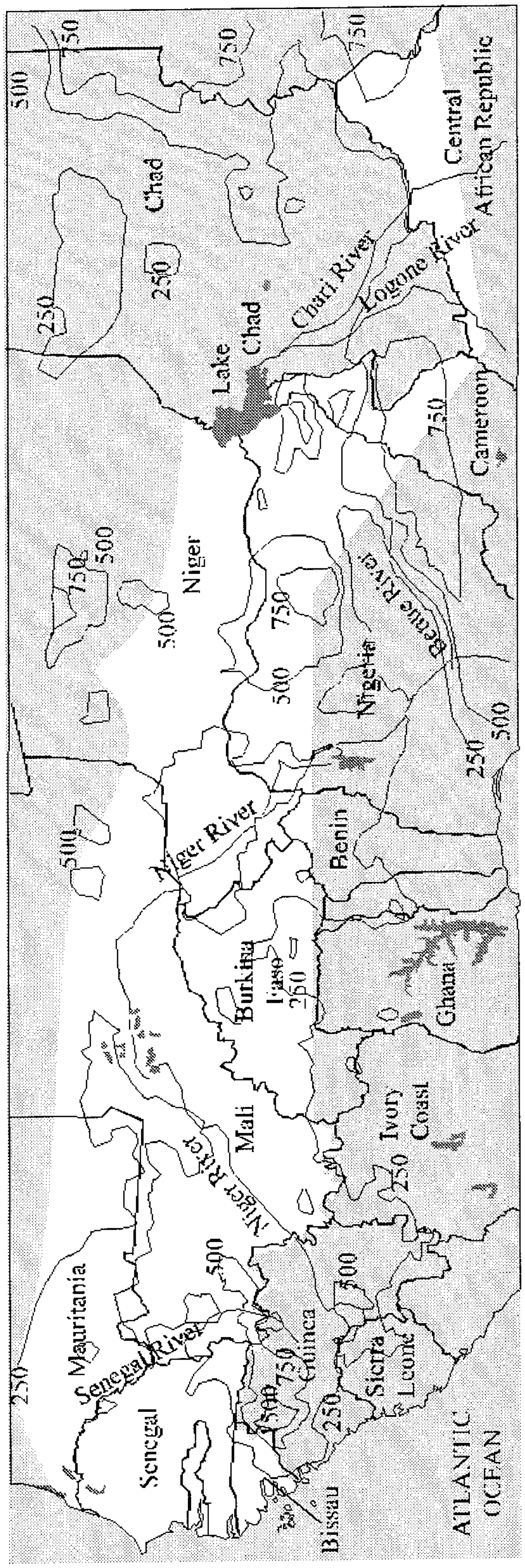


Figure 3-1. Topography of the Sahel. Contours in meters.

Rivers and Drainage Systems. The two major rivers in the Sahel are the Niger and the Senegal. Although both originate in the Guinea Highlands, they flow in opposite directions.

The Niger, a source of fertile farmland and commercial fishing along nearly its entire length, forms the longest river basin in West Africa and the third longest in Africa. It covers 4,200 kilometers as it runs northeast from its source into Mali, then turns southeast through Niger and into Nigeria, where it empties into the Gulf of Guinea. Its largest tributary is the Benou, which originates in the highlands of northern Cameroon and flows westward to join the Niger in central Nigeria.

The Senegal, which covers 2,500 kilometers, is the second largest river in the Sahel. The Senegal flows to the north and northwest from its source in central Guinea, forming the border between Senegal and Mauritania. It empties into the Atlantic Ocean in northwestern Senegal.

Lake Chad, at 228 meters above sea level in extreme northeastern Nigeria, forms the third major drainage system in the Sahel. Several smaller rivers have their origins in the surrounding plateaus and flow into the lake. The level of Lake Chad fluctuates widely during the year, depending on the flow rate of its two largest rivers, the Chari and the Logone. In recent years, the level of the lake has decreased dramatically. The Lake Chad basin has not filled up completely since 1975, and the lake is now completely surrounded by the Sahara. By 1993, the average surface area of the lake had been reduced to 17,800 km^2, less than one-third its former size. The lake is now composed of two basins separated by a north-south ridge known as the "Great Barrier." The ridge prevents circulation between the north and south basins. The northern basin often dries up completely at the end of the April and May dry season.

Vegetation. The northern Sahel is composed mostly of sand dunes covered with scrub grasses; increased precipitation to the south results in more clay soils and savanna grasses. Denser vegetation is found only in close proximity to river basins and along the narrow coastal band. Most of the Sahel supports savanna grasses, with scattered acacia, palm, and baobab trees. There is little continuous coverage, and there is a long-term tendency towards desertification, especially in the north. During the drought of 1972-73, the Sahara advanced south as much as 100 kilometers in some areas. Mangrove swamps, marshes, and lagoons are found in the coastal regions of Senegal and Gambia, as well as along the Niger and Senegal river basins. Desertification, however, has also begun to affect some portions of the Senegal River basin, with sand dunes now bordering the river in areas where the basin formerly extended 30 kilometers north of the river. Charney (1975) suggested that the trend towards increasing desertification may be self-perpetuating. He proposed a feedback mechanism in which the loss of vegetation in an area leads to an increase in albedo (a measure of the reflectance of a surface). This, in turn, causes a net radiation loss, which leads to sinking vertical motions and additional drying, thus perpetuating aridity.

MAJOR CLIMATIC CONTROLS OF THE SAHEL

The Azores High and the Saharan High. These two semipermanent high-pressure systems combine to block frontal systems from moving into the Sahel during northern hemisphere winter (see Figures 2-4a and b and 2-5a through d for their mean positions). Flow around these high-pressure centers gives rise to the northeasterly surface winds that dominate the Sahel from November through April and cause its dry season.

The Near Equatorial Trough (NET). Known locally as the "Intertropical Discontinuity (ITD)," the NET marks the boundary between the Saharan air mass and the South Atlantic air mass. Its position is responsible for the sharp discontinuity between the weather regimes of the Sahel during the wet and dry seasons. During the wet season (northern hemisphere summer), the NET moves to the north; surface winds become southwesterly as the Sahel is dominated by Atlantic air (see "Zone C, Summer," in Figure 2-8a). African Squall Lines are frequently generated in this moist, unstable air mass. The wet season ends as the NET moves back to the south; easterly to northeasterly surface winds dominate, returning the region to the influences of the hot, dry, and dusty Saharan air mass (see "Zone A, Winter" in Figure 2-8b).

Tropical Easterly Jet (TEJ) and Mid-Tropospheric Easterly Jet (MTEJ). The TEJ and MTEJ (described in detail in Chapter 2) combine to influence the development and movement of African Squall Lines through the Sahel. The high-level TEJ provides the outflow mechanism for convection, while the MTEJ steers squall lines westward across the zone.

The Harmattan. "Harmattan" is the name given to the northeasterly surface winds that blow throughout the dry season. The name is occasionally misapplied to the dust and haze that accompany the wind. Harmattan winds, generated by outflow from the Saharan High, cover a long desert track before they reach the Sahel; they are therefore hot and dry during the day, and cool at night. Visibility is often poor during the dry season because of the dust and haze carried in from the Sahara.

African (or Tropical) Squall Lines. Also commonly called "Disturbance Lines," or "Easterly Waves," African squall lines are the most important factors in the production of rainfall during the Sahel's wet season. Preferred locations for squall-line formation are the higher elevations of Southern Chad, the Jos Plateau, and central Ghana, where they tend to generate just to the west of the easterly trough at 700 mb. Once squall lines become organized, they invariably propagate westward at 25 to 30 knots. Although they are steered by the MTEJ, their speed of propagation is generally faster than the middle- and upper-tropospheric winds. Although isolated thunderstorms generally die out at night, African squall lines may remain active for several days and extend to lengths of 500 to 750 km; they occasionally develop into hurricanes after moving west into the Atlantic.

General Weather. As the NET moves northward with the onset of northern-hemisphere spring, Saharan air is driven to the north, marking the beginning of the Sahel's wet season, which is generally hot, cloudy, and humid. Although the air is moist and unstable up to about 6,000 meters, rainfall is seldom continuous; wet-season rainfall is almost entirely in showers associated with isolated air-mass thunderstorms and African squall lines or Easterly Waves.

July, August, and September are the wettest months at all locations in the Sahel. The rainy season begins earliest in the southeast, where squall lines begin to form over higher terrain in May. In the north, the migration of the NET is delayed; rain is not normally recorded until June or July. In some years, when the NET does not travel as far north (thus leaving the northern Sahel under the influence of the Saharan air mass), there is a drought. In northern Mauritania, for example, less than 5 mm of rain falls in 2 years out of 10. The wet season also begins later along the Atlantic coast, where the northward migration of the NET is delayed by the differential heating of the ocean and the land mass.

Wet-season temperatures are moderated somewhat by increased cloudiness and precipitation; the highest temperatures, therefore, occur earlier in the year rather than during northern-hemisphere summer, as might be expected.

The end of the wet season arrives earliest in the northern Sahel, where rain is scarce after September. The southeastern Sahel continues to receive rain through October.

Sky Cover. Skies are generally cloudy during the wet season, as shown by the high frequencies of ceilings in Figure 3-2. As a rule, the south is cloudier than the north, but there are exceptions over large areas of higher ground inland, such as the Jos Plateau.

The lowest cloud bases are associated with squall lines. As a squall line passes, ceilings are normally reported at 1,000 to 3,000 feet, lowering to 300 feet or less during rainshowers. Squall lines normally take 2-3 hours to pass a station, after which cloud bases gradually rise, first becoming stratocumulus at 1,000 to 2,000 feet, then turning into altocumulus at 10,000 feet or higher.

The tops of the cumulonimbus clouds that accompany squall lines generally reach 50,000 feet.

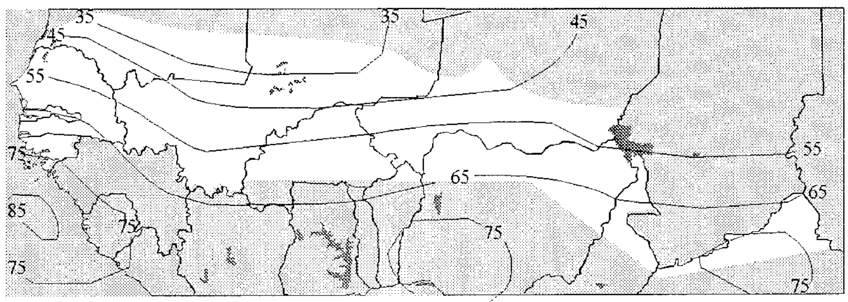


Figure 3-2. Percent Frequencies of Ceilings.

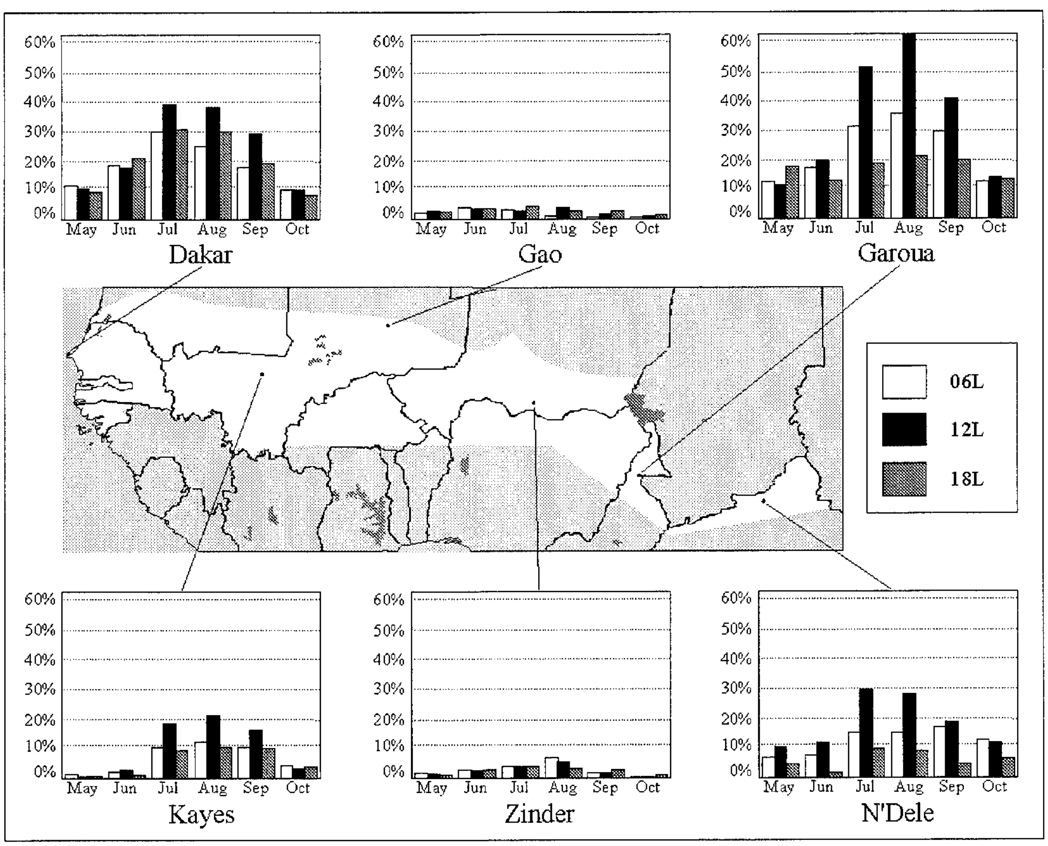


Figure 3-3. Wet-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. With the dry, dusty Saharan air held to the north by the NET, visibilities are generally much better during the wet season than in the dry, as shown by the low frequencies of visibilities below 4,800 meters in Figure 3-4. Saharan dust is confined to a haze layer that is suspended well aloft.

The poorest visibilities during the wet season (outside of rainshowers) are found in the extreme north, where the Harmattan regime lingers the longest (note, for example, the low-visibility frequencies for Gao in Figure 3-4).

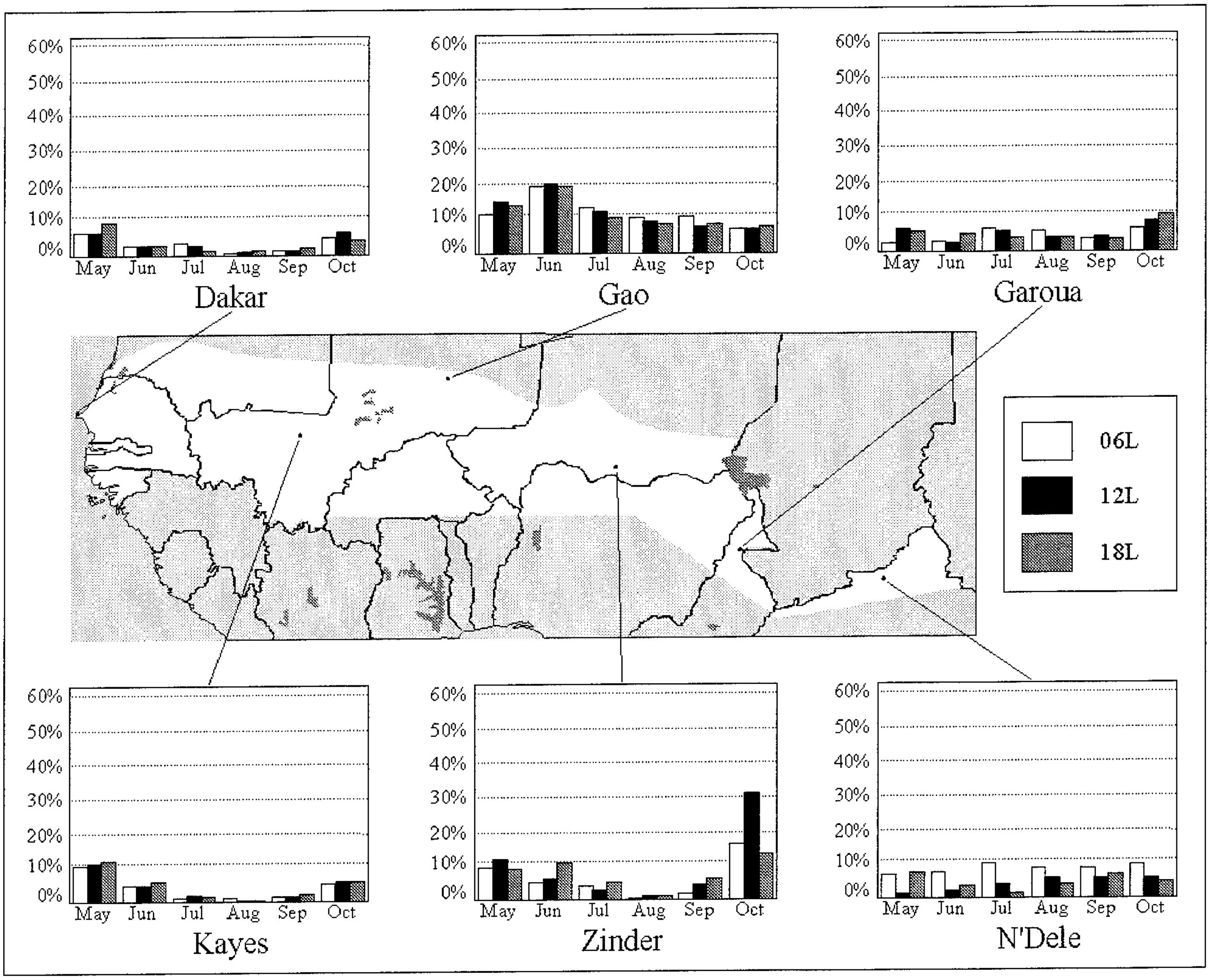


Figure 3-4. Wet-Season Percent Frequencies of Visibilities Below 4,800 Meters.

Winds. The wind roses in Figure 3-5 show the mean surface wind directions during August. A comparison of these directions to those for the dry season in Figure 3-13 explains the stark contrast in weather between the two seasons. During the wet season, the northeasterly Harmattan winds are replaced by southwesterlies as the Saharan High is replaced by a thermally induced low-pressure center. The dry Saharan air is held to the north, and the Sahel comes under the influence of a maritime tropical air mass. As during the dry season, the only exception to the wind-flow pattern occurs along the Atlantic coast, where more of a northerly component is apparent (see Dakar), reflecting the influences of the Azores High and the sea-breeze circulation.

Although mean surface wind speeds are generally lower during the wet season than during the dry season, the highest individual gusts are recorded during the wet season because of the frequent thunderstorm activity. Squall-line gusts reach 40 knots often, and they can reach 60 knots.

Aloft, with the MTEJ and TEJ in place, easterly flow (see Figures 2-13 and 2-14) provides the steering and outflow that govern the development and movement of squall lines. The mean position of the TEJ is just south of the Sahel, but it regularly moves northward, causing surges in convection as it moves over regions suitable for squall-line development.

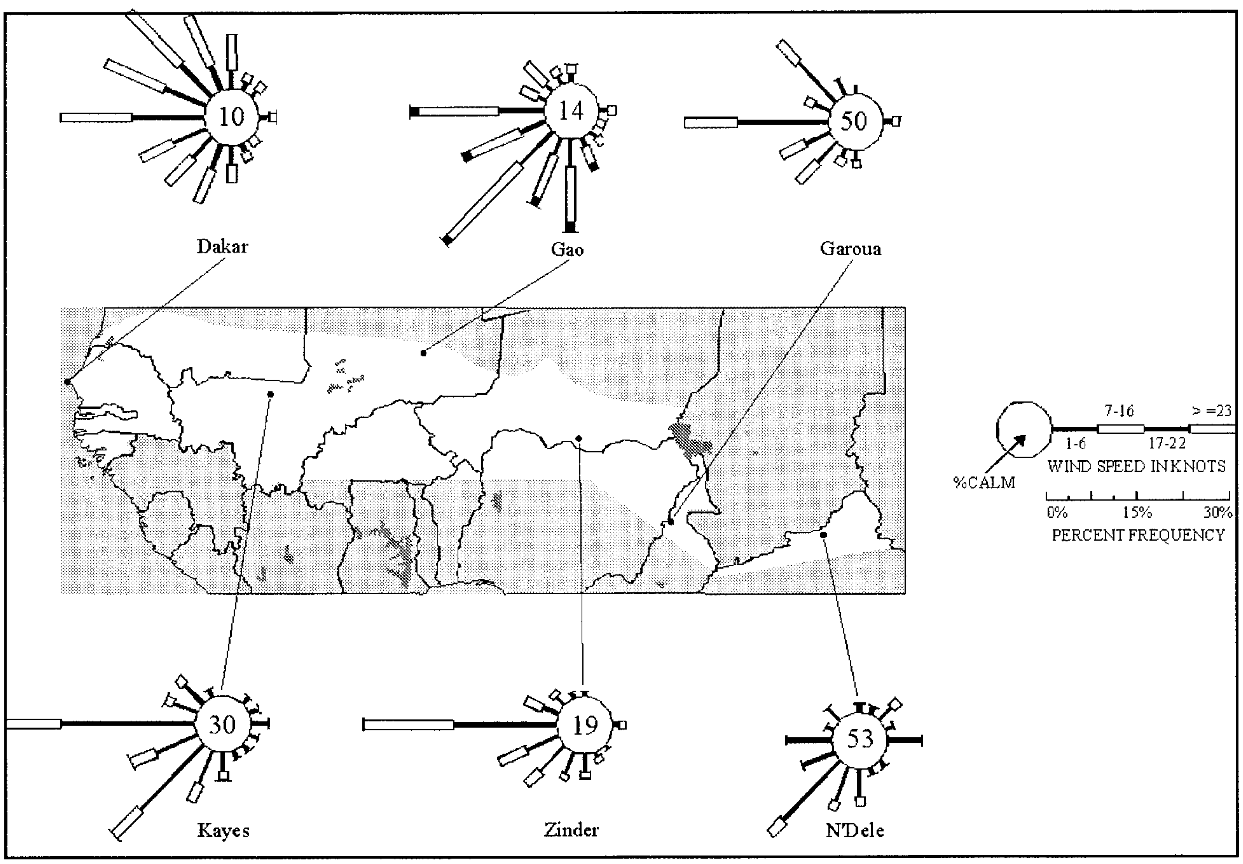


Figure 3-5. August Surface Wind Roses.

Precipitation. The amount of rainfall diminishes steadily from south to north. The 100 mm of rainfall during August shown over the northern Sahel in Figure 3-6 is very close to the total amount that region will receive for the year. Annual rainfall is near 500 mm across the mid-Sahel, while the southern part of the zone normally receives close to 1,000 mm a year. The extreme southern portion of the Sahel may occasionally experience a "little dry season" during August as the NET moves to its northernmost extent and completely out of the area.

The amount of rainfall received at any particular location in the Sahel varies widely from year to year; actual amounts may be very different from the "averages." For example, Koutiala (in southwest Mali) averages 28 mm of rain in April, but the actual rainfall received has varied from zero in 1937 to 156 mm in 1947. Precipitation ends by September or October (earlier in the north, later in the south) as the NET again moves south, returning the area to the dry, northeasterly winds of the Harmattan regime.

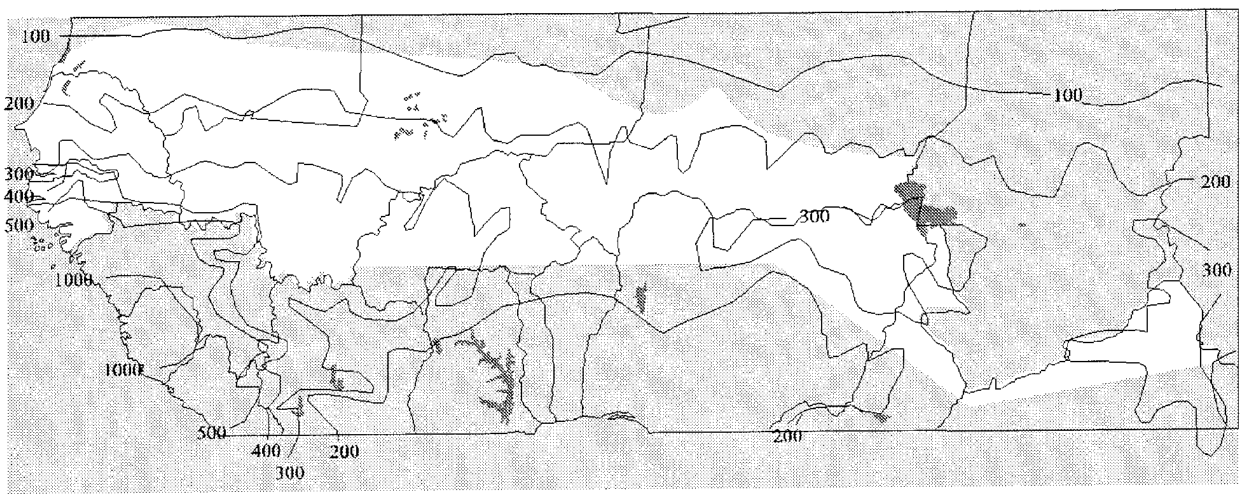


Figure 3-6. August Mean Precipitation (mm).

Thunderstorms. As the NET progresses gradually northward, isolated air-mass thunderstorms and African squall lines bring rain to the Sahel beginning in April or May, depending on latitude. The most rain falls during June, July, and August, when squall lines are most frequent. The area around the Jos Plateau in northern Nigeria, for example, averages 21 thunderstorm days (and gets 60% of its annual rainfall) during August (Hayward and Oguntoyinbo, 1987). Note in Figure 3-7 that there is a local rainfall maximum (300 mm) in the vicinity of the Jos Plateau; this corresponds to a preferred area for squall line development.

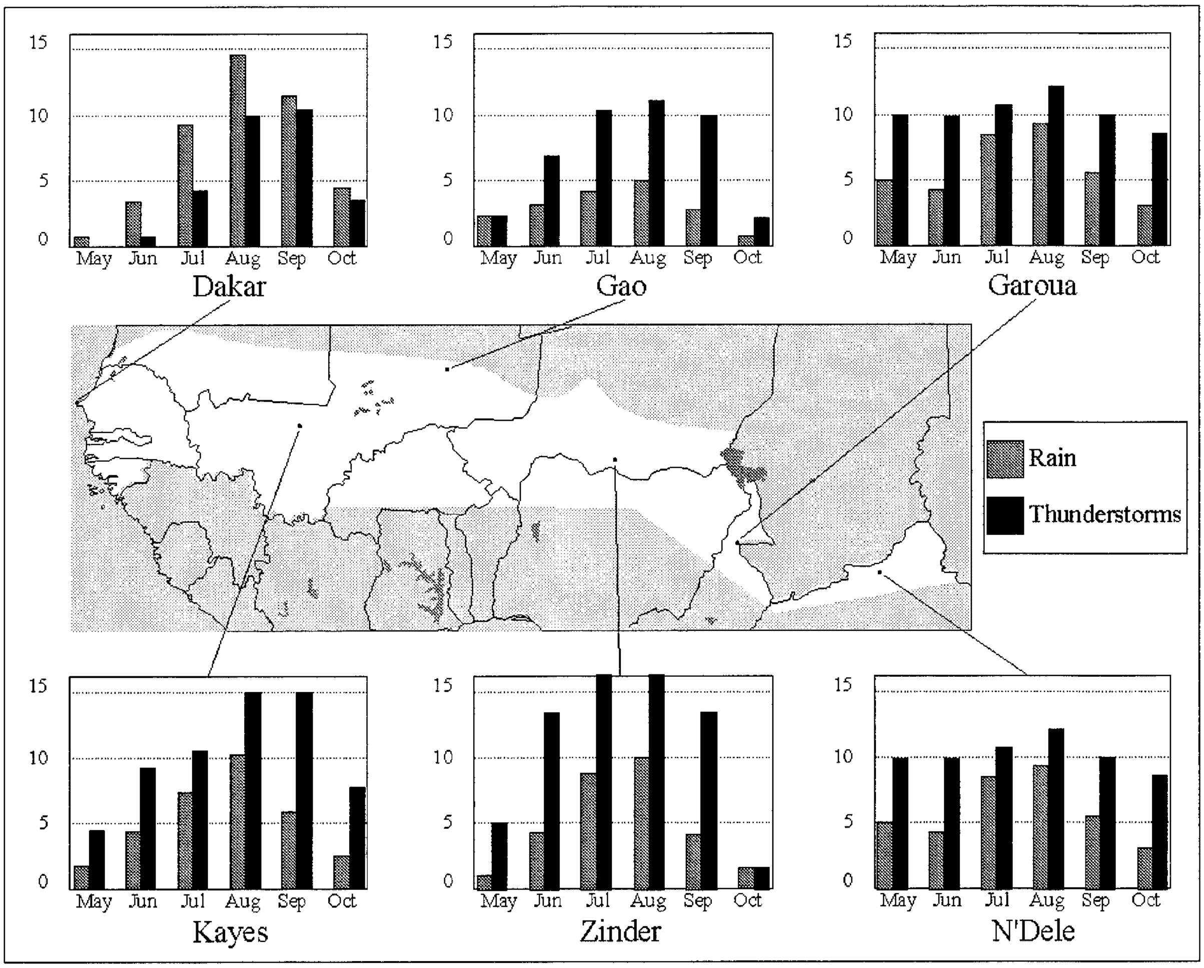


Figure 3-7. Wet-Season Mean Monthly Rain and Thunderstorm days.

Temperatures. Figures 3-8 and 3-9 show the mean monthly maximum and minimum temperatures during the height of the wet season. The persistently cloudy wet-season conditions keep daytime maximums low, similar to those of January. Without the rapid radiational cooling that occurs during the dry season, nighttime lows are higher during the wet season. Another important difference between seasons is that the highest wet-season temperatures are found to the north, where cloud cover and rainfall become increasingly rare. During the dry season, on the other hand, the highest temperatures are found to the south. Extreme temperatures at the height of the wet season approach 43° C in the north-central Sahel. Extreme highs along the coast and in the higher terrain of the eastern Sahel are near 37° C. Extreme minimum temperatures are between 18° and 20° C.

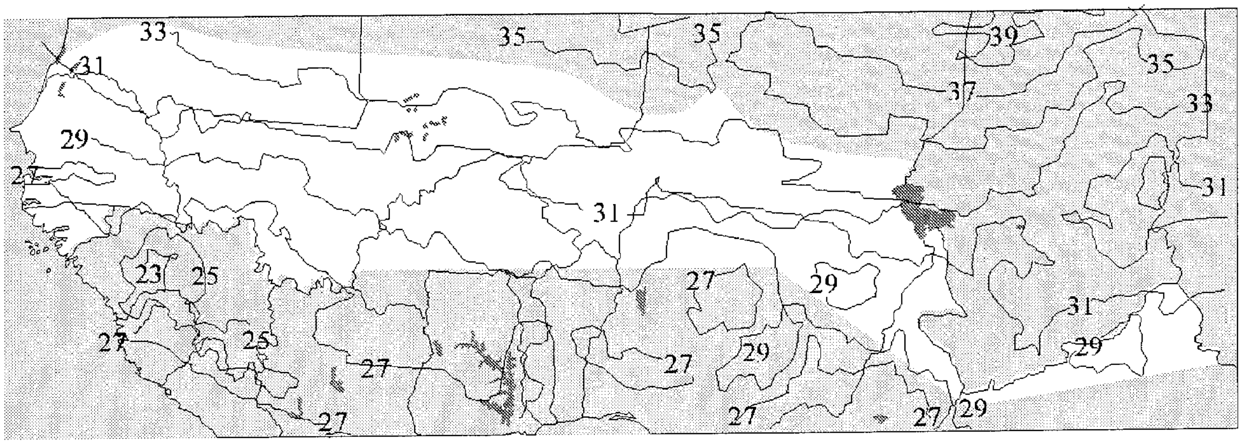


Figure 3-8. August Mean Maximum Temperatures (° C).

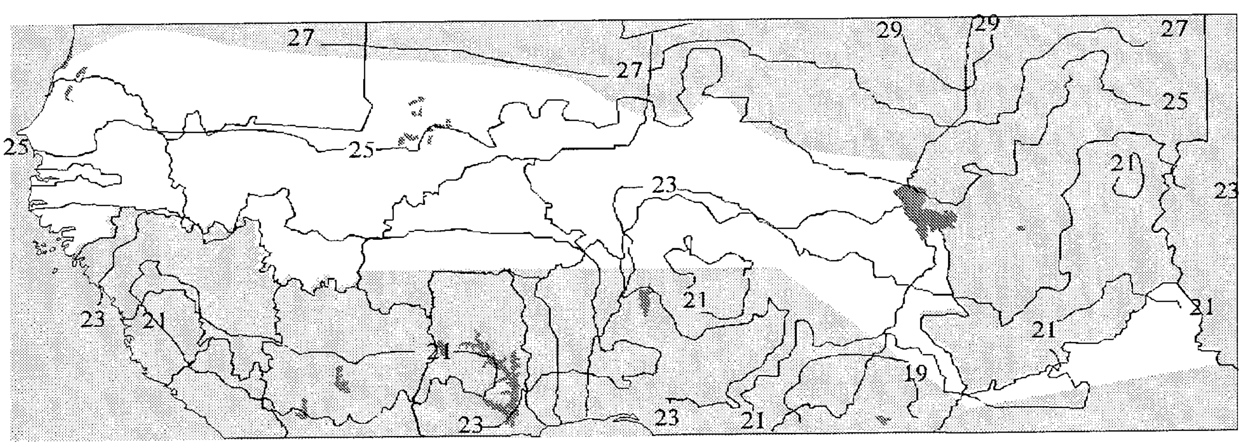


Figure 3-9. August Mean Minimum Temperatures (° C).

Other Hazards. The most significant hazards during the wet season are associated with the convective activity produced by African squall lines. The most common time for squall lines to develop is during peak heating periods between 1400 and 1700L. They persist for anywhere from 6 hours to 2-3 days and typically propagate east to west for 400 to 500 miles. Although locally called "tornadoes," there is no tornadic activity associated with these systems. There are, however, other significant hazards, including gusty winds, hail, severely restricted visibilities in showers, severe turbulence, and icing. Surface hail is most commonly observed when the squall lines move into the Fouta Djalon region. Aircraft icing has been reported well below the normal freezing level, which is 13,000 to 15,000 feet. Thunderstorm tops are normally at about 50,000 feet, but they occasionally exceed 60,000 feet.

General Weather. The dry season begins in November (earlier in the north), and runs through April (later in the north). Since the NET is south of the Sahel during the dry season, the area is dominated by the Harmattan winds (see the description of "Zone A" in the Chapter 2 discussion of the NET). The northeasterly surface winds bring hot, dry, and dusty conditions during the day, along with significant nighttime cooling. Little or no precipitation falls during the dry season. As soils continue to dry out through the dry season, duststorms and sandstorms become increasingly common, especially in the northern Sahel.

On rare occasions, a break in the monotonous pattern of dry and dusty days comes in the form of "Heug Weather," the local term for a pattern that develops when a front trailing from an Atlas Low manages to penetrate south as far as 15° N. Since moisture is usually only available at the upper levels, there is cloudiness associated with these fronts, but not much precipitation. Occasionally, however, there is enough low-level moisture from the Atlantic to bring heavy rain (especially to coastal areas) during normally dry periods.

Sky Cover. Cirrus is fairly common over the Sahel, but there are very few dry-season low or middle clouds. Ceilings are rare during the dry season, but they are slightly more common to the south and along the coast, as shown in Figure 3-10. Figure 3-11 shows that the frequencies of ceilings below 3,000 feet is very nearly zero from November through January. As the dry season ends in March or April, low ceilings are first observed in the higher elevations of the eastern Sahel and along the Atlantic coast. The low ceilings in the east are associated with convection, as African Squall Lines begin to develop. Along the coast, ceilings are commonly stratiform.

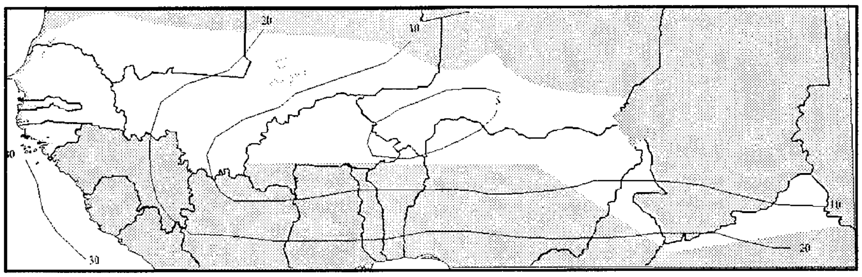


Figure 3-10. January Percent Frequencies of Ceilings.

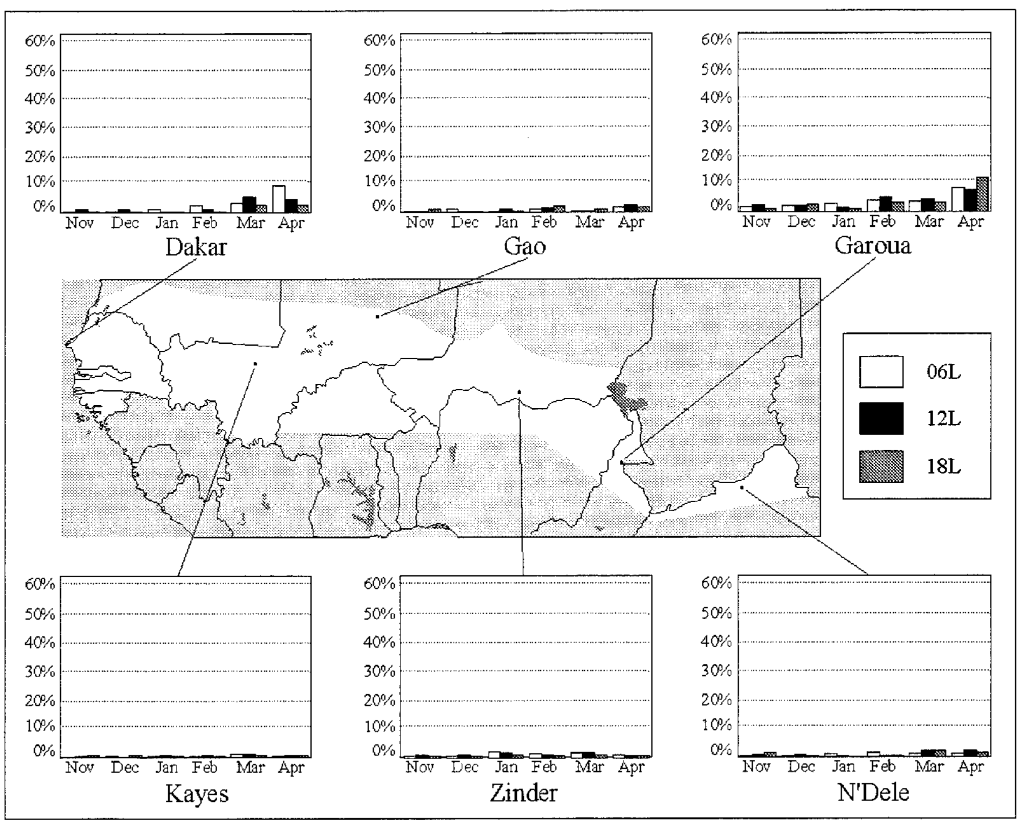


Figure 3-11. Dry-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Harmattan winds, laden with dust and haze, contribute to the relatively high frequencies of low visibilities shown in Figure 3-12. Dust and haze are worst toward the end of the dry season. In northern Nigeria, for example, visibilities are below 3,000 meters 37% of the time during January and February (Adetunji et al., 1979). A diurnal pattern of increasing and decreasing visibility develops during Harmattan duststorms. As winds decrease during the night because of the loss of surface heating, dust settles out of the atmosphere under the radiation inversion, resulting in good early morning visibilities. Shortly after sunrise, however, convective turbulence begins to mix the layers and pick up dust from the ground. By 0700L, visibility is again poor (typically 1,600-4,800 meters). The worst visibilities (800-1,600 meters) are usually reported at about 0830L. After that, there is steady improvement as dust becomes more evenly distributed in the haze layer. By 1600L, visibilities are 4,800-8,000 meters, improving through the night.

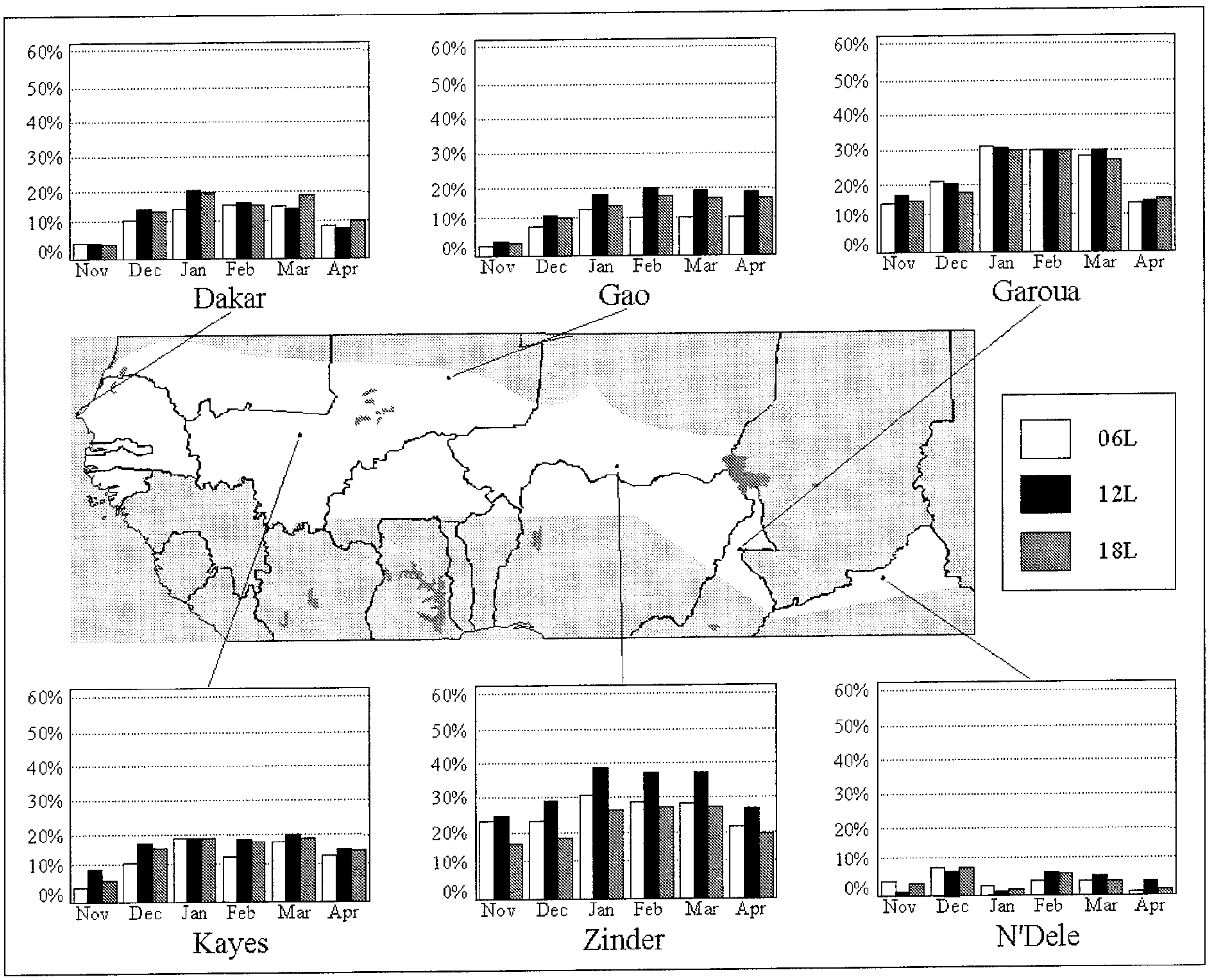


Figure 3-12. Dry-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. Under the influence of the Saharan High, surface winds almost always blow from the east to northeast throughout the dry season. The only exception is found along the Atlantic coast, where the increased influence of the Azores High is reflected in the dominance of northerly winds shown at Dakar in Figure 3-13. Wind speeds associated with the Harmattan are about 8 to 12 knots during the day, dropping to 5 knots or less at night. Speeds are slightly higher in the north. The highest dry-season speeds are found near Dakar due to the persistent northerlies off the Azores High, enhanced by the sea breeze. Prevailing winds aloft are also from the east to northeast up to about 8,000 feet; speeds range from 15 to 45 knots.

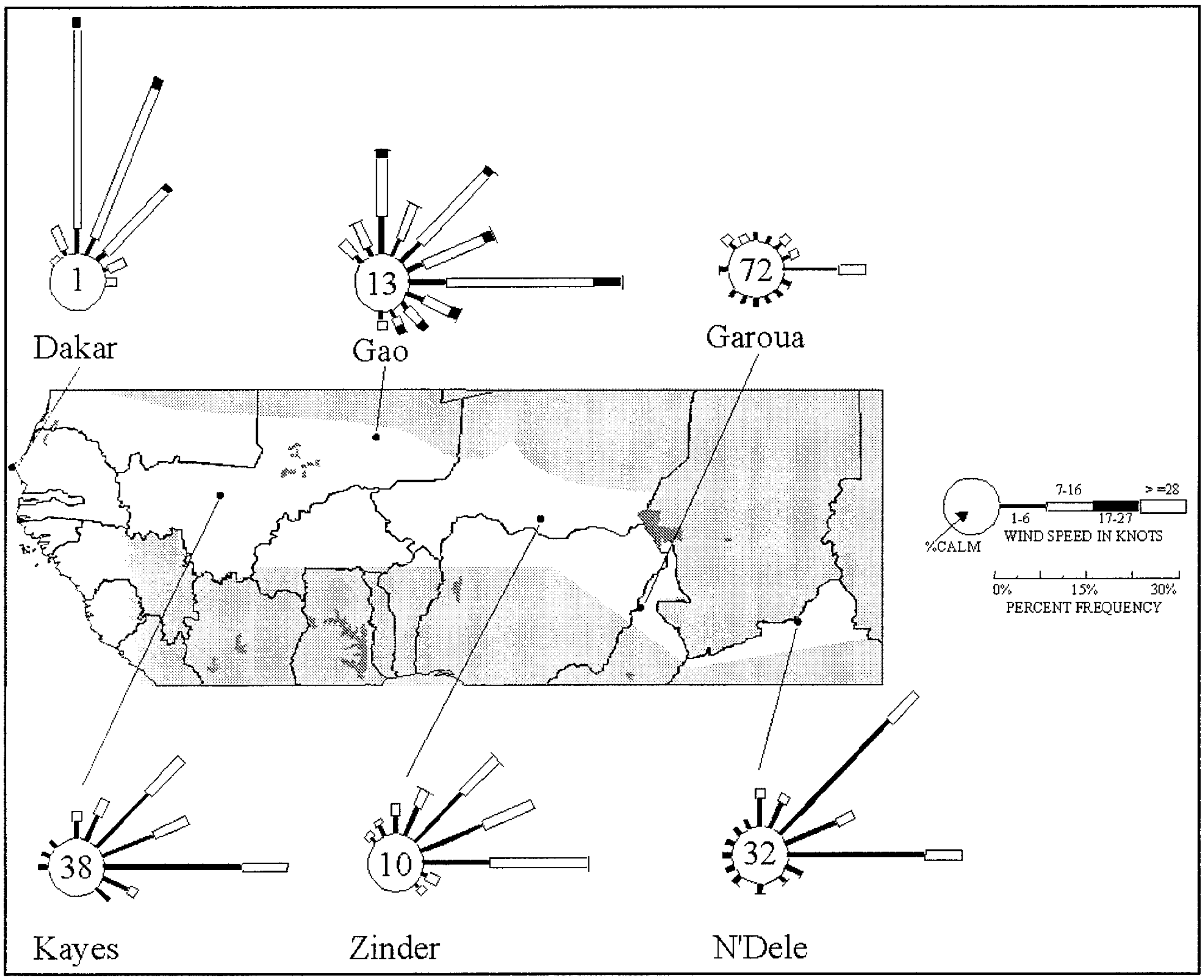


Figure 3-13. January Surface Wind Roses.

Precipitation. Figure 3-14 makes it clear that rainfall is extremely rare during the dry season. The eastern Sahel gets less than 1 millimeter of rainfall during January; the average is only slightly higher near the coast. The rain that does fall is associated with the rare "Heug Weather" discussed previously, during which a frontal system trailing from an Atlas Low manages to penetrate south. As the dry season comes to a close, the rains return earliest to the eastern Sahel as convection begins to develop over the higher elevations in March or April.

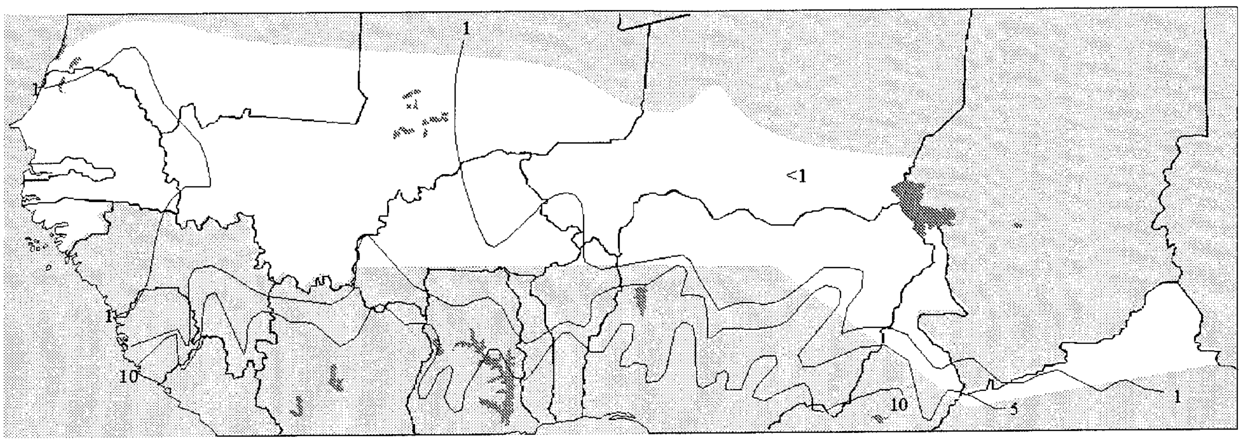


Figure 3-14. January Mean Precipitation (mm).

Thunderstorms are very rare during most of the dry season, but African Squall Lines begin to develop over the high terrain of the eastern Sahel toward the end of the season (see Figure 3-15).

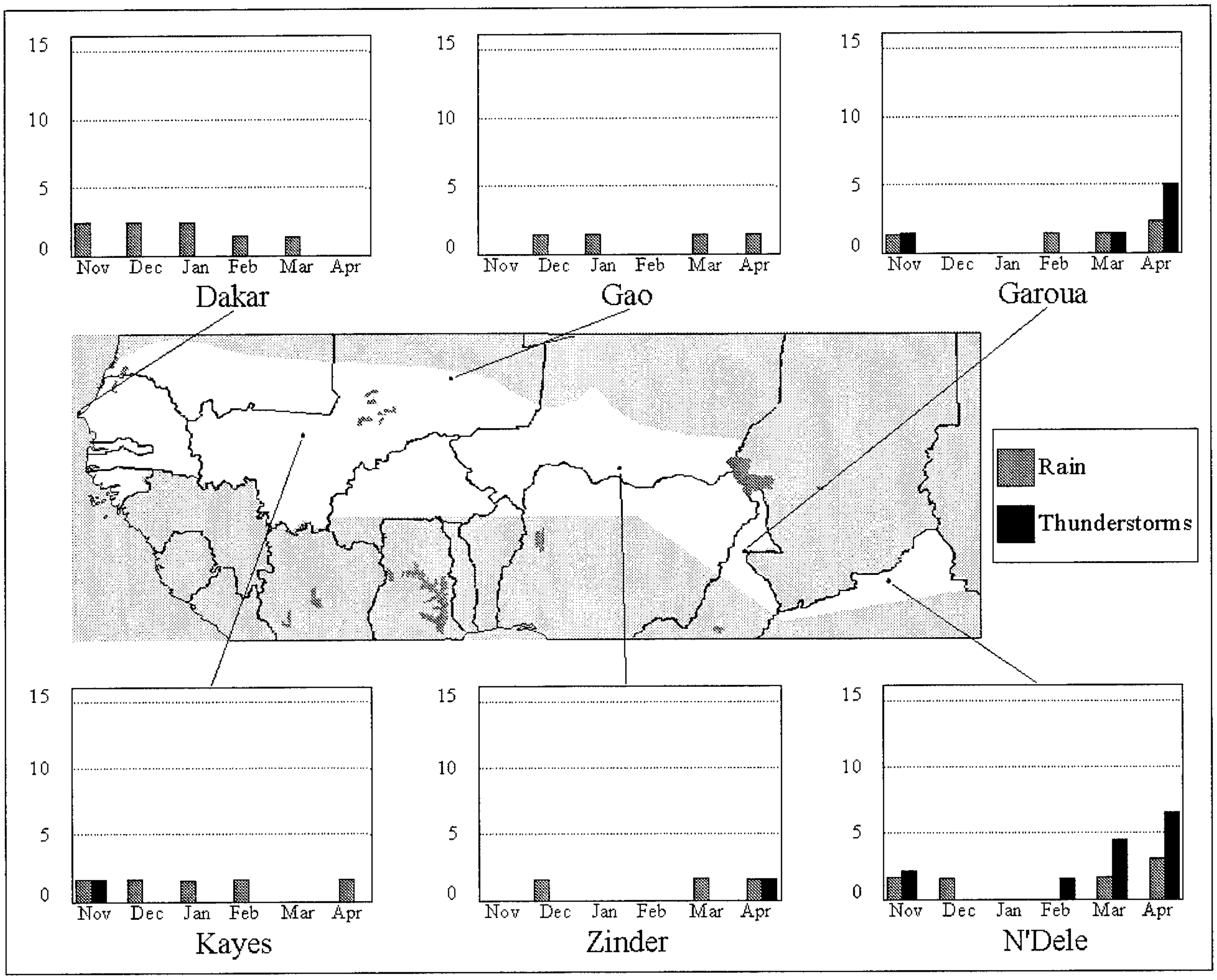


Figure 3-15. Dry-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. The highest mean maximum temperatures in the Sahel are observed toward the end of the dry season. In the south, temperatures are highest during March and April, when they may reach extremes of 43° C. In the north, the warmup occurs slightly later, with highs occasionally approaching 47° C during April and May. Along the Atlantic coast, where the ocean moderates temperatures, highs are normally near 38° C.

Because the low humidities allow rapid radiational cooling at night, the Sahel's lowest temperatures are observed during the dry season. From December through February, extreme lows can reach 8° C in the north, 10° C in the south, and 13° C along the coast. Figures 3-16 and 3-17 show mean maximum and minimum temperatures, respectively, during January, the height of the dry season.

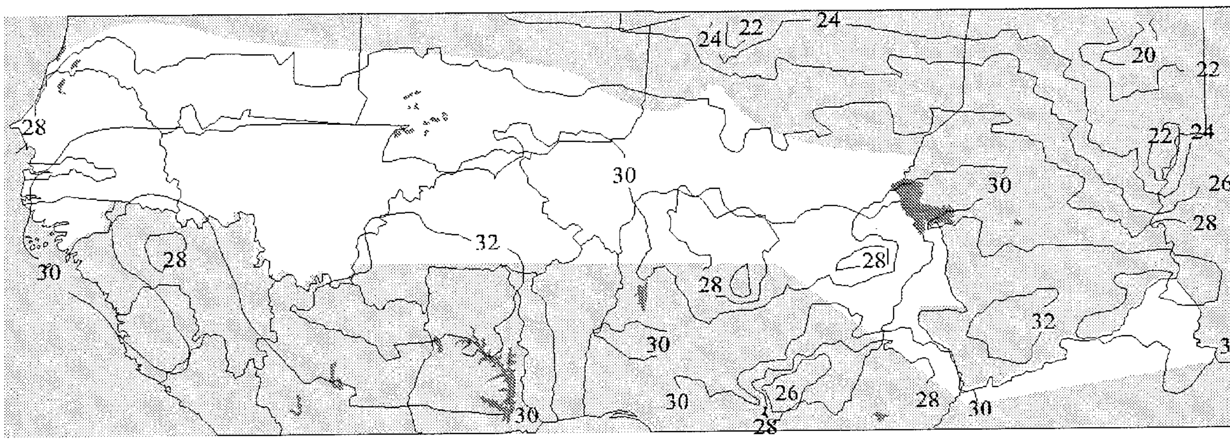


Figure 3-16. January Mean Maximum Temperatures (° C).

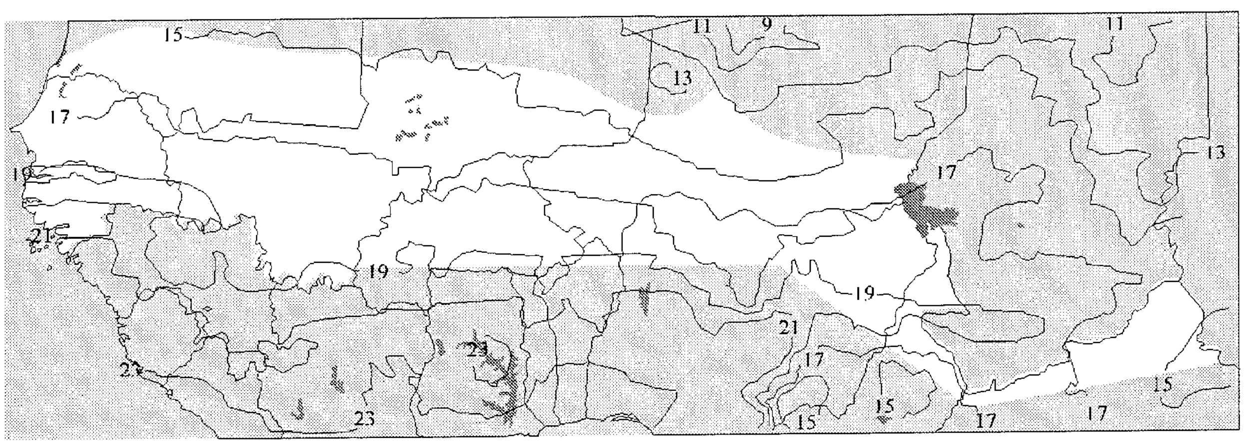


Figure 3-17. January Mean Minimum Temperatures (° C).

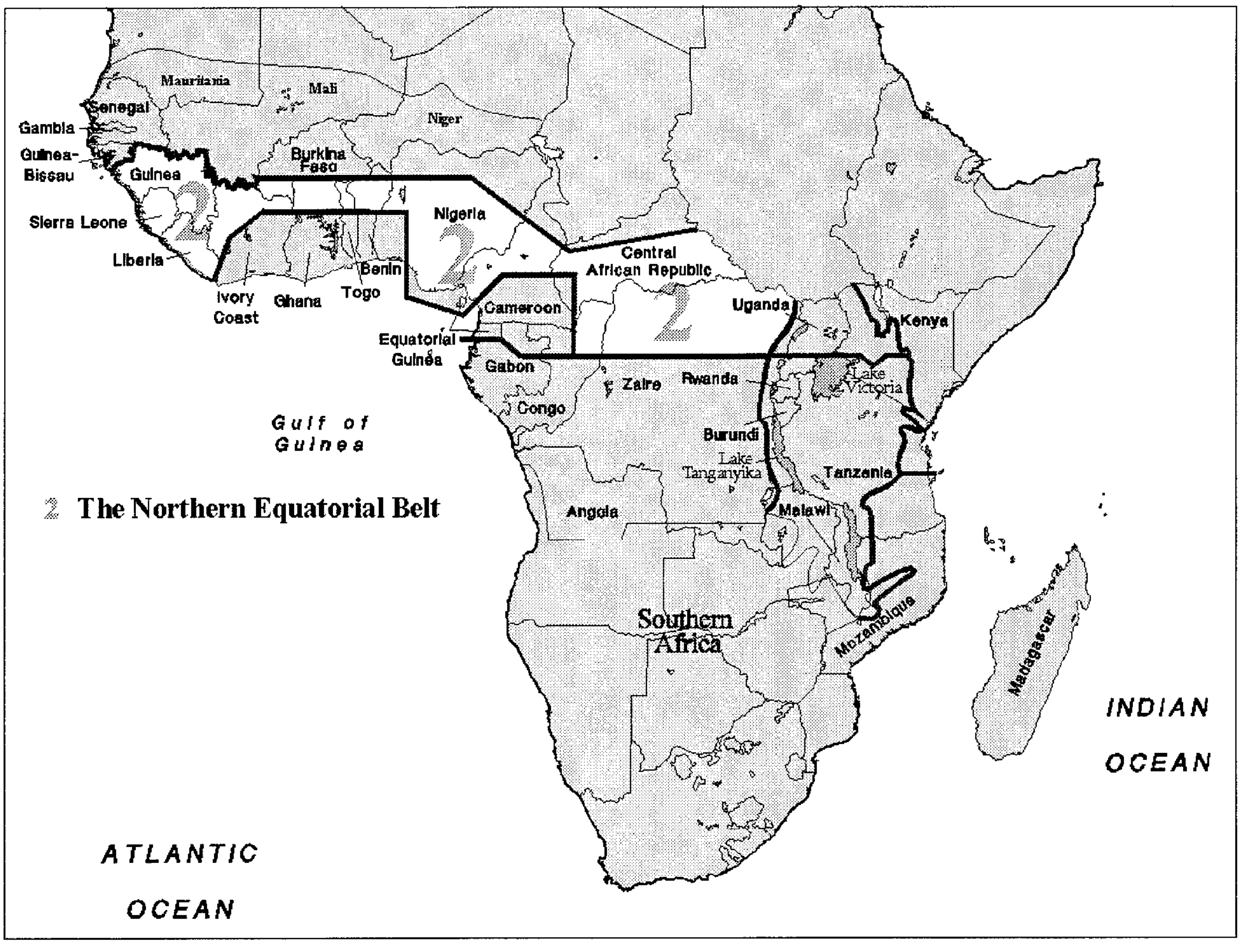
Other Hazards. Duststorms are common when solar heating is strong and mean wind speeds are above 15 knots. They become more common toward the end of the dry season when the soil is driest. Visibilities in storms can approach zero. Duststorms usually last for about 2 hours, but they can persist for up to 24 hours. Sandstorms are composed of heavier particles that remain suspended below 6 feet and settle quickly; they can also occur, especially in the northern portions of the Sahel. The ever-present dust and low humidity cause dry skin, sore throat, and cracked lips. The dust can also contribute to radio signal degradation.

Recent research suggests an increasing trend toward more frequent dust storms in the Sahel. For example, Goudie and Middleton (1992) published data showing that the number of duststorm days at Nouakchott, on the southeastern coast of Mauritania, rose from about 10 in 1970 to near 80 in 1985. The trend is also apparent at Dakar, where the average number of duststorms rose from 10 a year in the late 1960s to 40 a year in the late 1970s.

Chapter 4

THE NORTHERN EQUATORIAL BELT

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) for the long and narrow climatic zone that runs nearly all the way across west and central Africa. This zone, as shown below, comprises all of Guinea, Sierra Leone, and Liberia, as well as the northern parts of the Ivory Coast, Ghana, and Togo. It also includes Central Benin, Southwestern Nigeria, Southeastern Cameroon, Northern Congo, Northwestern Zaire, and the southern part of the Central African Republic.



NORTHERN EQUATORIAL BELT GEOGRAPHY

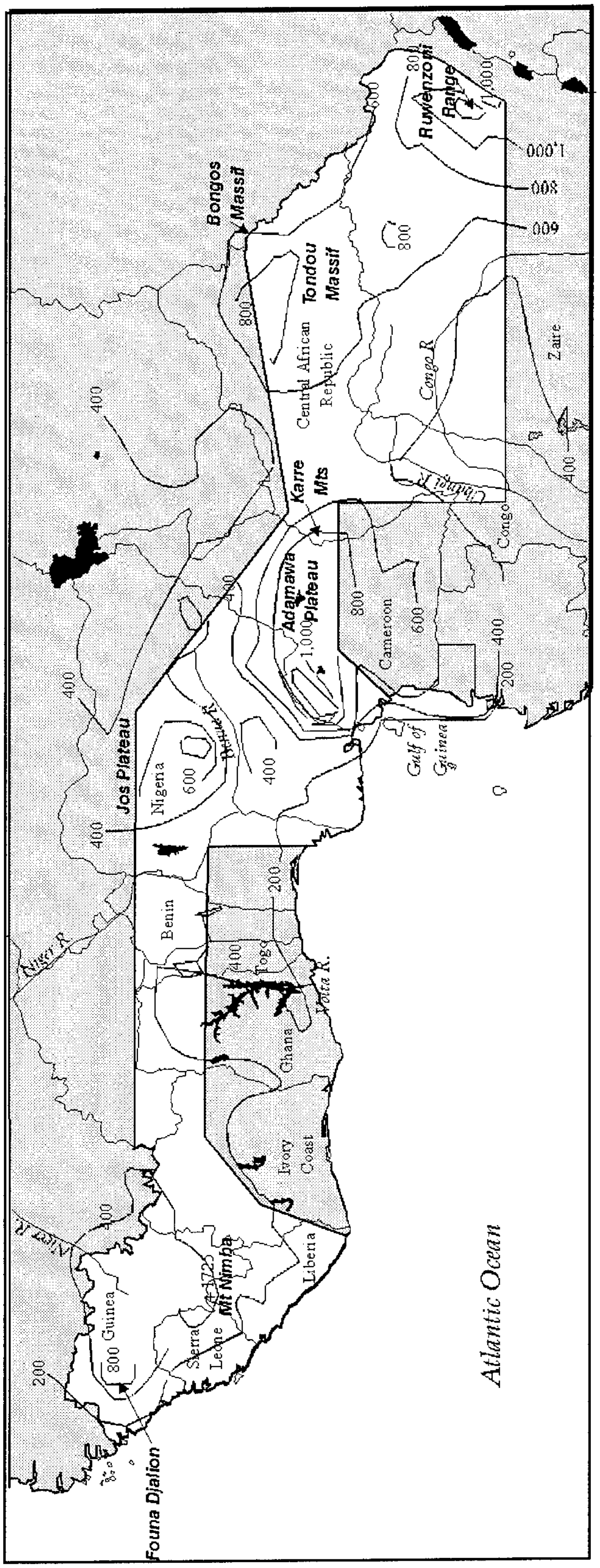


Figure 4-1. Topography of the Northern Equatorial Belt. Contours in meters.

NORTHERN EQUATORIAL BELT GEOGRAPHY

Seasons. The Northern Equatorial Belt lies between the semiarid highland regions of northeast Africa and the equatorial rain forests of West Africa and the Congo Basin. It also lies within that part of Africa that, according to Ramage (1972) has a monsoon climate (see Figure 2-6). The north-south movements of the Near Equatorial Trough (NET) determine the beginnings, ending, and durations of the wet and dry seasons. When the NET moves north of the area, moist, unstable maritime tropical air moves in and the wet season begins. Conversely, when the NET moves southward and allows dry, continental air to move into the area from the northeast, the dry season begins. The wet season is from April to October, with a dry season from November to March. In some areas, there is a shorter (December-February) dry season (less than 50 mm mean monthly rainfall).

Boundaries. The reversal of the seasons at the equator marks the northern boundary of this climatic zone, while the southern boundary is defined by the 1,500-meter contour. As shown in Figure 4-1, the geographic boundaries of the zone are necessarily more complicated. The northern boundary follows the northern border of Guinea and the Ivory Coast to Burkina Faso, then runs across Ghana, Togo, and Benin to central Nigeria. It then turns southeast across Nigeria and Cameroon and east to the border of the Central African Republic. The eastern boundary follows the eastern borders of the Central African Republic and Zaire to 30.5° E, then cuts across eastern Zaire to the equator at 28.5° E. The southern boundary follows the equator to 16° E in the northeastern Congo, then turns north to the Central African Republic and runs across Cameroon to the Gulf of Guinea. It then runs along the coastlines of Cameroon and Nigeria to 5° E, turns north and east across Nigeria, Benin, Togo, and the Ivory Coast, then southwest to the Atlantic coast between Liberia and the Ivory Coast. The western geographic boundary is marked by the coastlines of Liberia, Sierra Leone, and Guinea.

Major Terrain Features. Plains dominate West Africa except for isolated high plateaus and mountains in Guinea, Sierra Leone, Liberia, Cote d'Ivoire, Togo, Nigeria, and Cameroon. The coastline from Guinea south to Liberia is flat, low-lying, sandy, and broken by marshes and mangrove swamps. Terrain rises rapidly from the Guinea coast to the Fouta Djallon Plateau; the highest point is Mount Nimba (1,752 meters).

Sierra Leone is hilly in the north with plains in the south. Liberia is also hilly, with a flat highland between 200 and 500 meters. Cote d'Ivoire is mostly high savanna; over half the country is above 350 meters. In contrast, more than half of Ghana lies below 150 meters, but hills along its western border rise to 450 meters.

An ancient plateau with elevations between 60 and 450 meters covers more than half of Togo. Central and northern Benin's terrain is flat lowland with low hills and marshlands.

The main physical features of Nigeria are the Niger Delta in the south, the Adamawa Plateau along the eastern border, the Niger and Benue river valleys, and the Jos Plateau in the north. Central Cameroon terrain rises from south to north and is dominated by the Adamawa Plateau at between 750 and 1,350 meters.

The vast central plains of the Central African Republic separate three of Africa's major river basins: the Congo, Lake Chad and its tributaries, and the Nile. The plains rise to over 1,300 meters in the vicinity of the Bongos Massif in the northeast and the Tondou Massif in the east and southeast. In the west, the Karre Mountains form a granite range that slopes eastward into sandstone plateaus.

The central depression of the Congo River Basin, with an elevation of 300 meters, is the main feature of northern Zaire. High plateaus rise in all directions from the basin, reaching elevations of 900-1,200 meters to the east and northeast, where they merge with the Ruwenzoni Range along Zaire's eastern border.

NORTHERN EQUATORIAL BELT GEOGRAPHY

Rivers and Drainage Systems. The main rivers in the Northern Equatorial Belt are the Volta, Niger, Benue, Ubangi and Congo; all drain into the Atlantic Ocean.

The Volta River, Ghana's main drainage system, flows southward into the Gulf of Guinea. It also includes Lake Volta, one of the world's largest artificial reservoirs.

The Niger River starts in Guinea approximately 500 kilometers from the Atlantic Coast. After running northeast from Guinea into Mali, it turns southeast through Niamey and along the northeastern border of Benin before it flows into central Nigeria and is joined by the Benue River.

The Benue River originates in eastern Nigeria and flows southwest to its intersection of the Niger.

The Niger River flows southward into the Niger Delta at the Gulf of Guinea.

The Ubangi River forms part of the border between Zaire and the Central African Republic. After turning southward, it becomes the border between Zaire and the Congo Republic where it flows into the Congo. At Bangui, the Ubangi rises about 6 meters during the rainy season.

The Congo River, at about 4,700 kilometers in length, is one of the longest rivers in the world, second only to the Amazon in drainage area and discharge rate. It rises in the high plateaus of southern Zaire and flows north into the Northern Equatorial Belt, where it turns southwest to empty into the Atlantic.

Vegetation. Guinea, Sierra Leone, and Liberia share similar vegetation. Backed by tropical rain forest, these countries are heavily wooded with several species of trees; mangroves and oil palms line the coasts. The Fouta Djallon is mostly open with wooded areas near its many streams. Cote d'Ivoire's rain forests contain valuable teak and mahogany, but high grasslands dominate in the north.

In northern Ghana, savanna dominates, with tall grass and various species of acacia. Togo and Benin have mostly savanna type vegetation. Nigeria has mangrove and freshwater swamps along the Niger Delta; inland, there are rich tropical forests with several species of trees including the iroko, mahogany, and obeche.

Farther south, tropical grasslands with baobab trees and tamarind dominate. As the landscape becomes more open, narrow forest zones and various types of acacia are present. Vegetation in Cameroon is also varied, with rich tropical rain forests in the south and mangrove swamps along the coast. Central Cameroon has deciduous trees, while the north has short grasses.

The Central African Republic lies largely in the savanna zone of Africa, but dense rain forests grow near the Ubangi River.

Northern Zaire, dominated by the Congo River Basin, has vast rain forests. Savanna dominates the plateau areas east and northeast of the basin.

MAJOR CLIMATIC CONTROLS OF THE NORTHERN EQUATORIAL BELT

The Near Equatorial Trough (NET). In this region, the NET (also referred to as the "Intertropical Discontinuity") takes on the characteristics of a monsoon trough that divides the dry Saharan air (tropical continental) to the north from the moist south Atlantic air (tropical maritime) to the south. The NET moves north and south during the year in response to changes in the relative strength of the Azores, Saharan, and South Atlantic Highs. The position of the NET determines the onset and duration of the Northern Equatorial Belt's wet and dry seasons. Its mean position is completely north of the zone from April to October, bringing the zone its wet season (see Figures 2-6c through 2-6i).

The Azores High. During northern-hemisphere winter, this semipermanent high blocks Atlantic lows and frontal systems from the western part of the Northern Equatorial Belt. Its interaction with the South Atlantic High forms the NET, discussed above. Mean Azores High positions are shown in Figures 2-4a & b.

The Saharan High. This feature, caused mainly by strong radiative cooling, is present from October to May. It doesn't normally block weather systems, but it can join with the Azores High to produce a strong area of high pressure; strong outflow winds from the northeast blow across the Sahara toward the Northern Equatorial Belt. Mean Saharan High positions are shown in Figures 2-4a & b.

The South Atlantic High. Outflow from this control meets the outflow from the Azores High and Saharan High to form the NET. It is the major source of moisture during the wet season as the NET is pushed northward across the Northern Equatorial Belt by moisture-laden outflow. Mean South Atlantic High positions are shown in Figures 2-4a & b.

The Tropical Easterly Jet (TEJ). Oscillating between 5 and 20° N at about 200 mb, the TEJ's mean position is across the northern part of the Northern Equatorial Belt at about 10° N. Changes in the TEJ cause surges in convection.

The Mid-Tropospheric Easterly Jet. This mid-level jet is present from May to October, the wet season in the Northern Equatorial Belt. It steers African waves and squall lines westward across the zone and is also important in squall-line development.

Ocean Currents/Sea Surface Conditions. The Equatorial Countercurrent and the Guinea Current bring warm waters to the Gulf of Guinea along the south coast of west Africa eastward to Cameroon, where they increase the amount of moisture in wet-season outflow from the South Atlantic High. See Figure 2-2 for mean sea-surface temperatures.

SPECIAL CLIMATIC FEATURES OF THE NORTHERN EQUATORIAL BELT

African Squall Lines. These wet-season features are most common in sub-Saharan Africa between 5 and 15° N from June through September. They develop due to convective instability along the NET, as the deep, dry Saharan easterlies override the moist, shallow southerly monsoonal flow. Steered by the MTEJ, they move westward at 20 to 35 knots, but they can move at up to 50 knots. In the Northern Equatorial Belt they occur most frequently 100-200 km south of the NET's surface position during the wet season. Nigeria's Jos Plateau is a preferred area for squall line development. Surface wind gusts up to 80 knots are possible with these squall lines; intense, cold downdrafts with speeds of 20-30 knots over flat terrain can raise large amounts of dust and sand and lower visibilities to near zero. Hail is common in high terrain.

Land/Sea Breezes. All coastal areas of the Northern Equatorial Belt have land/sea breezes to some extent the year-round. The sea breeze is strongest from June to August. The land breeze is strongest in January.

Harmattan. The Harmattan is the dry, northeasterly wind caused by outflow from the Saharan High during the dry season. During its long trajectory over the desert, the Harmattan picks up large amounts of dust and sand. The resulting haze is often called "Harmattan Haze." The Harmattan is hot during the day and cool at night. With the onset of the Harmattan, relative humidities can drop from near 100% to as low as 30-40% in 2-3 hours; temperatures remain constant.

General Weather. The dry season is mostly hot and dry with little cloud cover. Harmattan winds and the resulting Harmattan Haze affect the entire zone to varying extents. The dry season begins when the NET moves southward and allows dry continental air to move into the area from the northeast. Although the durations of the wet and dry seasons vary from 3 to 5 months at different locations, the dry season usually runs from November through March. In part of the zone, however, there is a shorter dry season (December-February) during which mean monthly rainfall is 50 mm or less. The areas affected by this shorter dry season include Liberia, a small part of Sierra Leone adjoining Liberia, coastal Nigeria, and northern Zaire and the Congo Republic north of the equator. As a result of the shorter dry season, vegetation flourishes in this "mini-zone."

Sky Cover. The least cloud cover is generally found in the northern parts of the zone, due to the dry continental air mass that covers the area from the northeast. Coastal areas and the Congo Basin area remain south of the NET throughout the dry season; they see more cloudiness due to the maritime tropical air mass that prevails there. Ceiling frequencies in January vary from 10-20% in the north to 40% in coastal areas and 60-70% near the equator (see Figure 4-2). Low ceilings are rare except at coastal locations such as Monrovia, Port Harcourt, and Mamfe, where morning and afternoon ceilings are below 3,000 feet (see Figure 4-3). January, in the middle of the dry season, is the least cloudy month of the year.

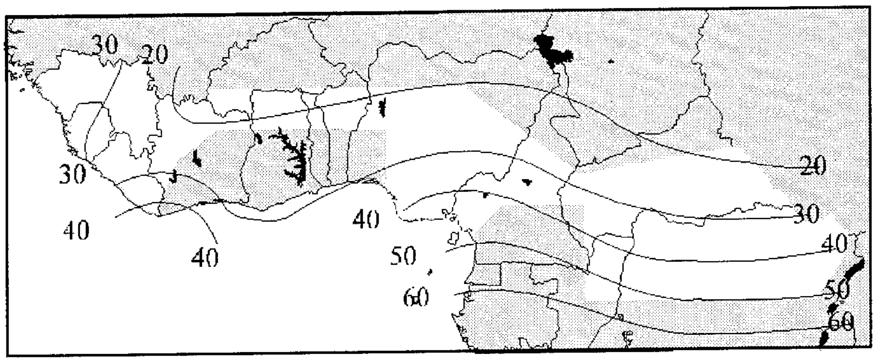


Figure 4-2. January Percent Frequencies of Ceilings.

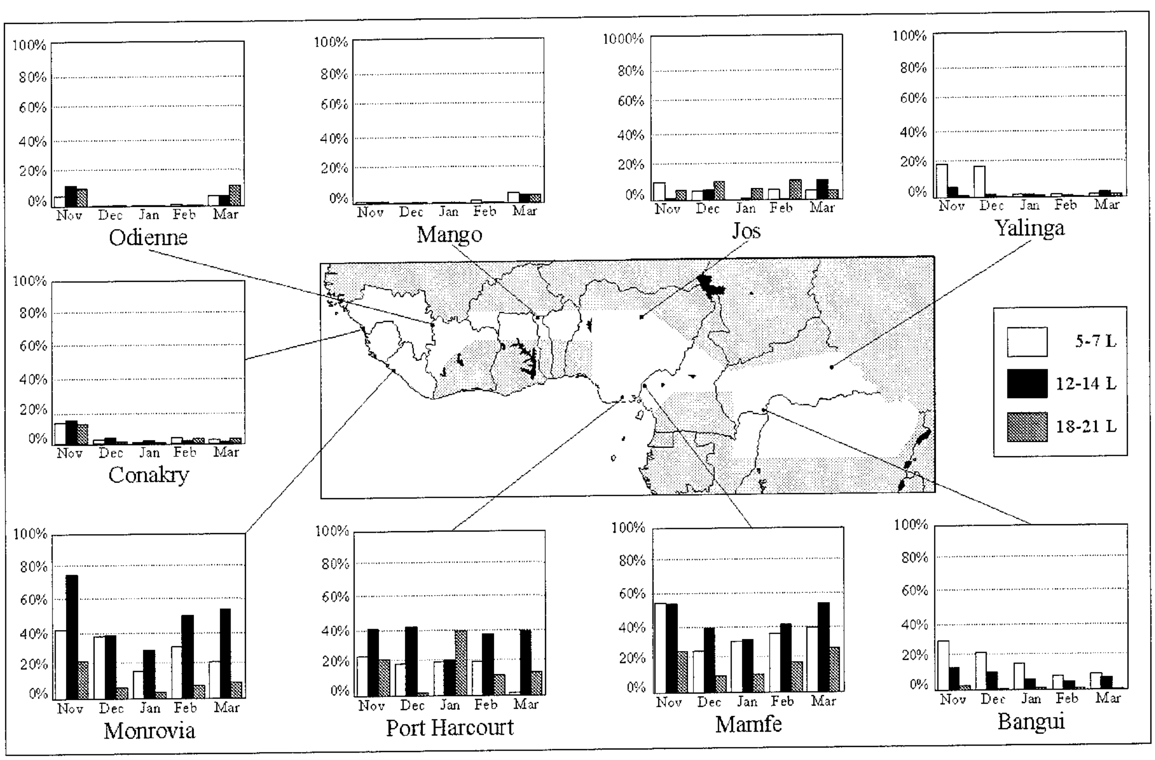


Figure 4-3. Dry-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Harmattan winds lower visibilities as they suspend dust and sand in the atmosphere near the surface, particularly in the north, where visibilities are below 4,800 meters up to 40% of time (see Figure 4-4). At Jos, on the Jos Plateau in northern Nigeria at over 1,200 meters, visibilities are below 4,800 meters 20-30% of the time.

North of the NET, the haze layer can extend from the surface to about 2,000 meters. South of the NET, the haze is lifted aloft to about 4,000 meters; in-flight visibility can be as low as 2,000 meters. Early morning fog is common near coasts and in the Congo River Basin, where visibilities are below 4,800 meters 50-80% of the time during December and January.

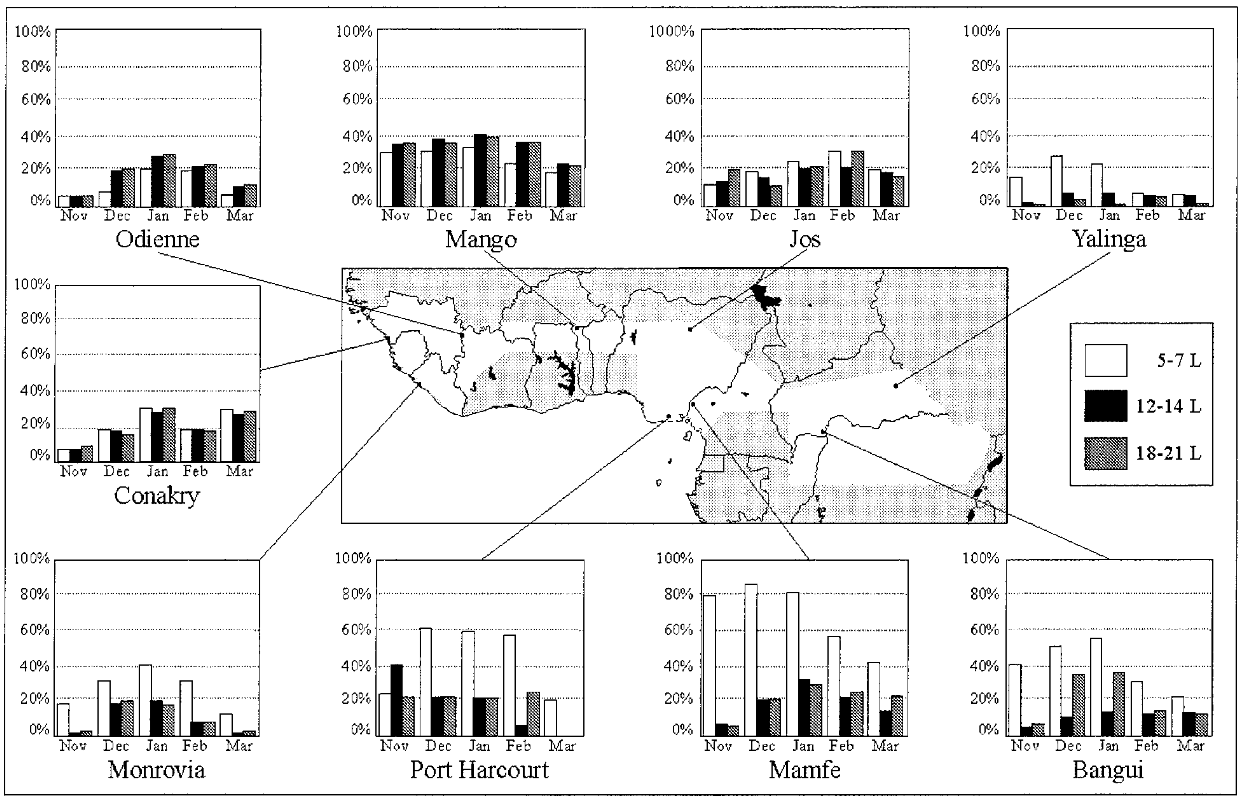


Figure 4-4. Dry-Season Percent Frequencies of Visibilities Below 4,800 meters.

SurfaceWinds. Northerly to northeasterly winds prevail across the northern part of the zone; they are generally light and variable at night. Speeds seldom exceed 16 knots, except over the higher terrain near Jos, where speeds can reach 27 knots (see Figure 4-5). In the eastern part of the zone in the area of the Congo Basin, winds are normally westerly to southwesterly at 5-7 knots in the afternoon. At coastal locations south of the NET, winds are westerly to southwesterly and reinforced by the year-round sea breeze. The land breeze is strongest in January, but only at about 5 knots.

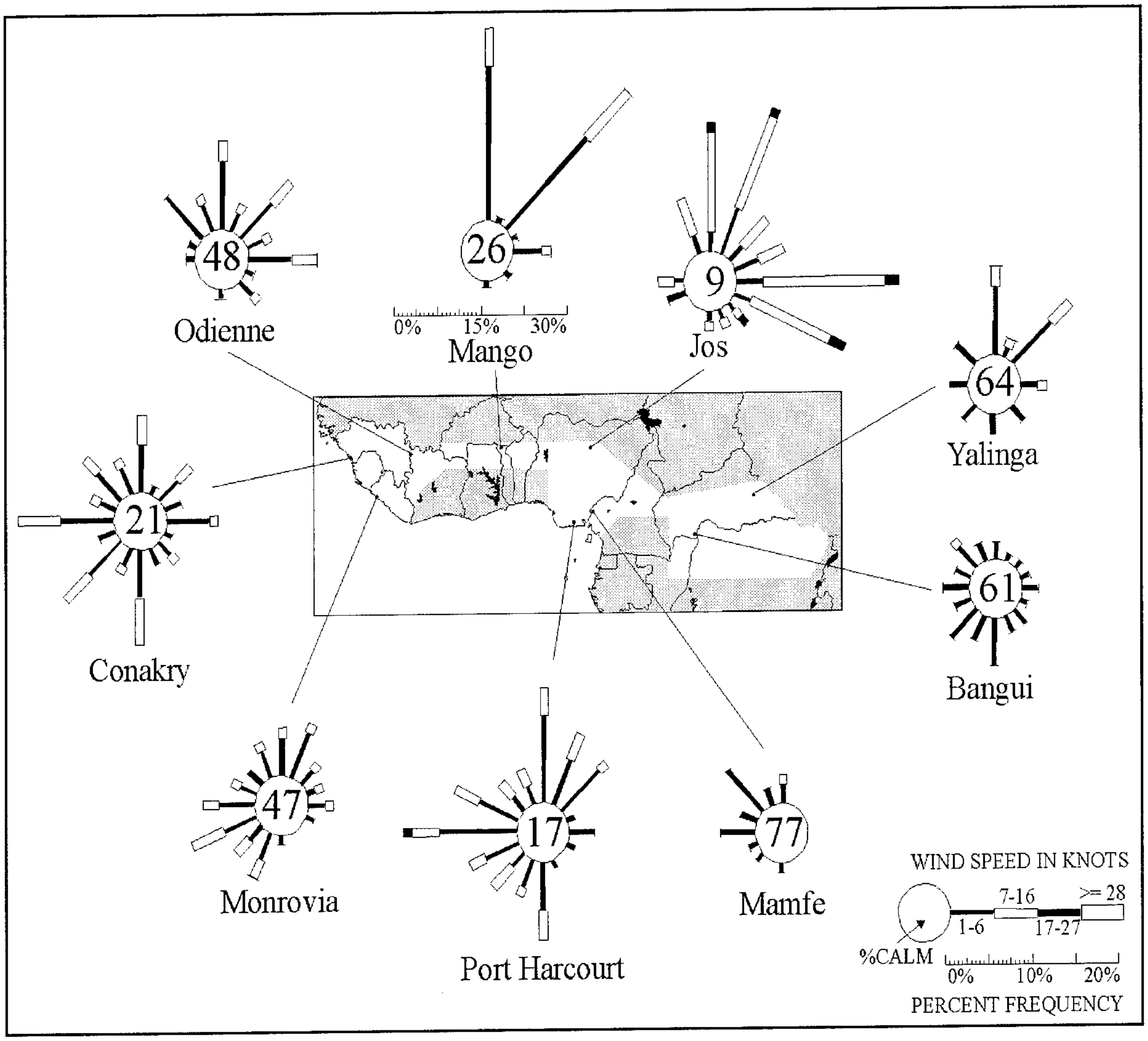


Figure 4-5. January Surface Wind Roses.

Winds Aloft. Middle and upper-level flow is generally from the east. Low-level flow north of the NET is northerly to northeasterly, but southerly south of the NET.

Figure 4-6 shows that the January mean 850-mb winds are north to northeast at Bangui, but northeasterly to southeasterly at 700 mb and above.

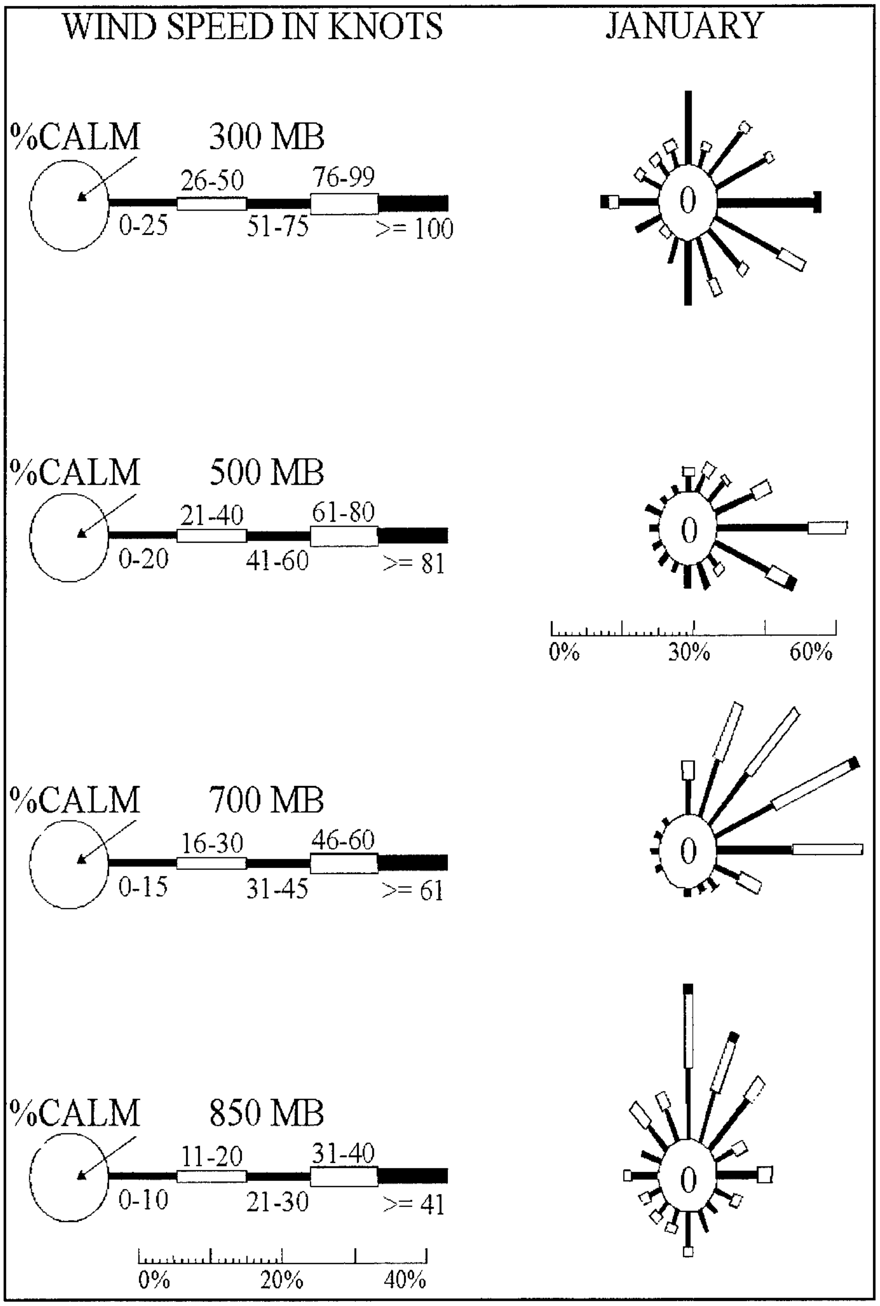


Figure 4-6. January Upper-Air Wind Roses at Bangui, Central African Republic.

Precipitation. December and January are the driest of the year. As little as 1 mm falls during January in the north (see Figure 4-7), but near the equator and in coastal regions, January rainfall averages 100 mm or more. Most rain falls as showers. Even those areas that record the most rainfall see rain on only about 5 days a month, mostly early and late in the dry season (see Figure 4-8).

Thunderstorms. Generally rare, thunderstorms are most common at the beginning and end of the season. As Figure 4-8 shows, the southwestern coast and the Congo Basin have up to 10 thunderstorm days during November and March.

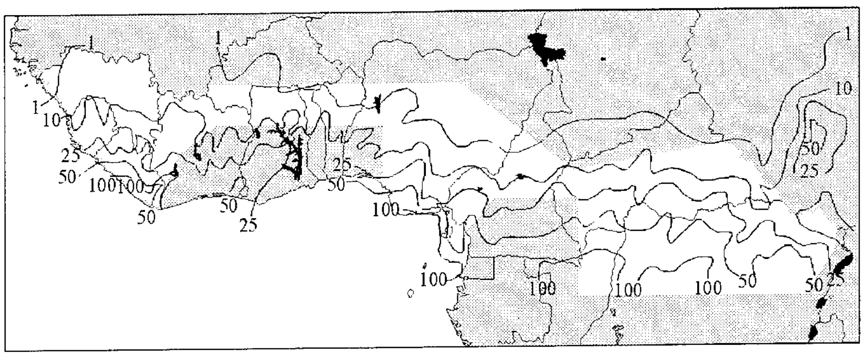


Figure 4-7. January Mean Precipitation (mm).

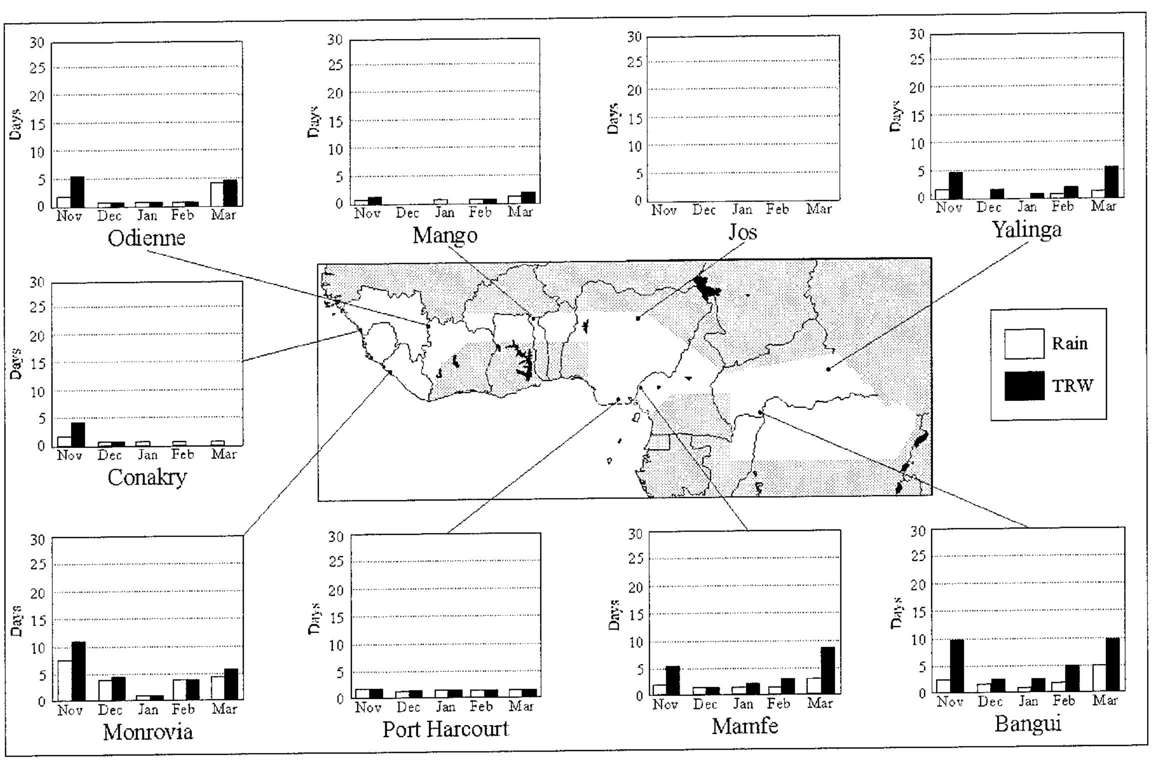


Figure 4-8. Dry-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. The lowest temperatures are usually recorded in January or early February; the highest, in late February or March. Temperatures are lower along coasts and at higher elevations.

Mean maximum temperatures in January are near 31-33° C in the north. Extreme highs can reach 45° C in the interior. Mean minimum January temperatures vary from 19° C in the north to 23° C in the south.

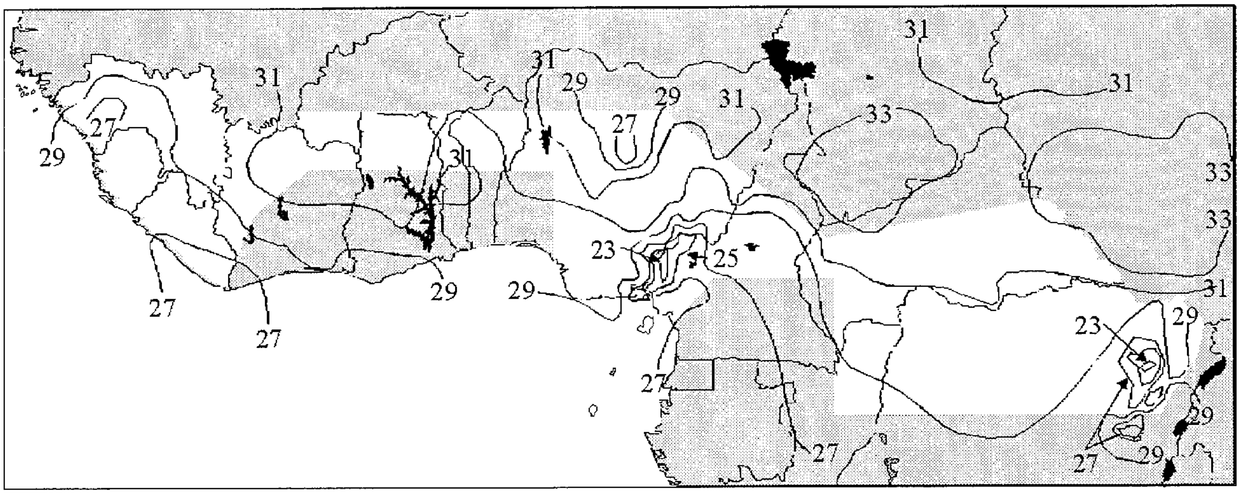


Figure 4-9. January Mean Maximum Temperatures (° C).

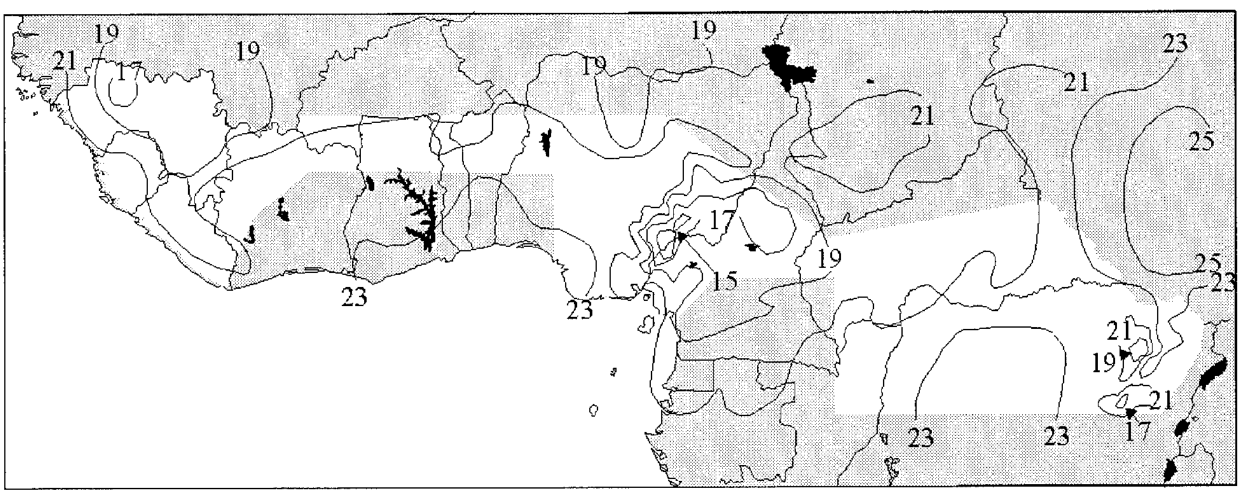


Figure 4-10. January Mean Minimum Temperatures (° C).

General Weather. The wet season is generally cloudy, hot, and humid. The movement of the NET northward across the Northern Equatorial Belt pushes the dry, continental air northward. By April, the NET usually lies north of the Northern Equatorial Belt, and the wet season has begun.

Sky Cover. July and August are the cloudiest months of the year. Ceiling frequencies are greatest near the equator, where ceilings are present 80% of the time. Although the extreme north has the lowest frequency of ceilings, they still occur 60% of the time (see Figure 4-11).

Ceilings below 3,000 feet are most common near the coasts in the moist tropical maritime air. For example, Figure 4-12 shows that at Monrovia, afternoon ceilings are below 3,000 feet over 80% of the time during July and August. At interior locations in the east, such as Bangui and Yalinga, low-ceiling frequencies are the least, occurring 20% of the time or less.

"Frontal" cloud lines caused by the convergence of the sea breeze and the prevailing southwesterlies are visible daily off the coast from Liberia south to Nigeria.

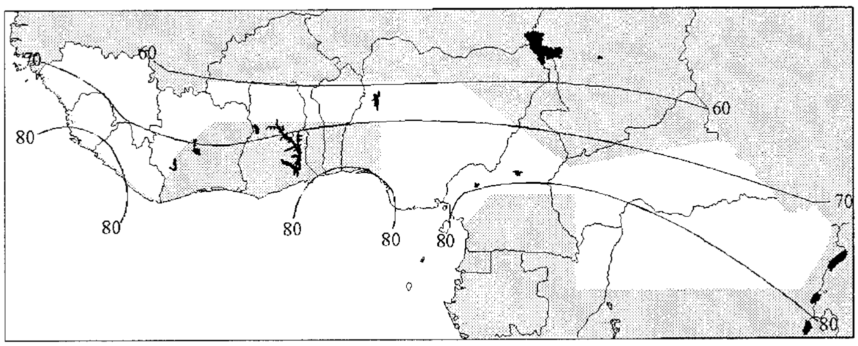


Figure 4-11. July Percent Frequencies of Ceilings.

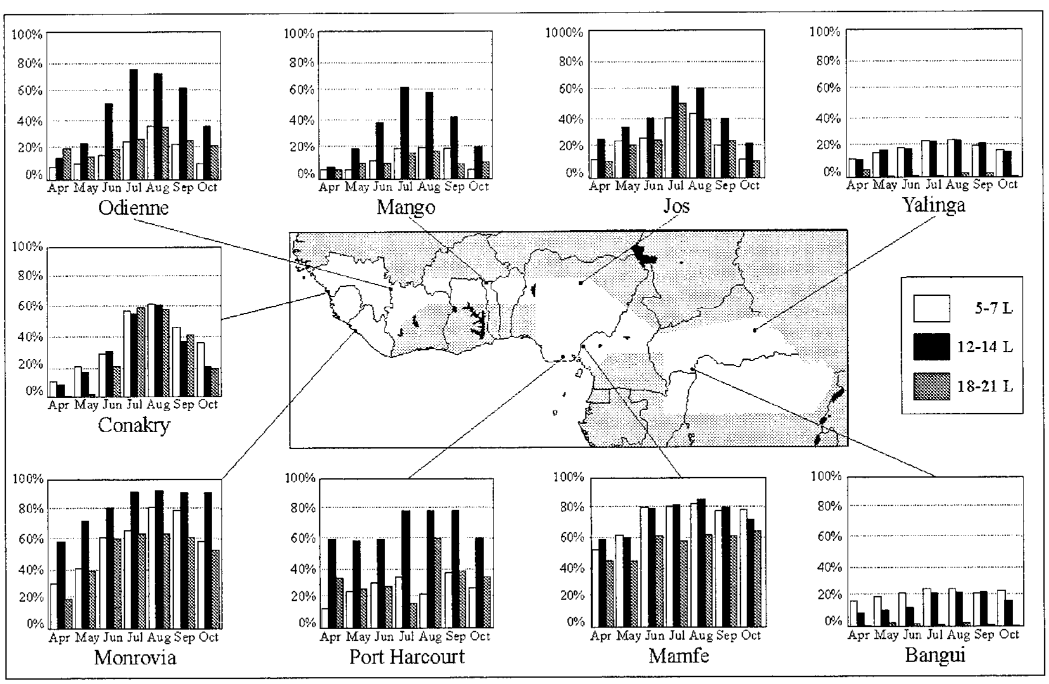


Figure 4-12. Wet-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Visibilities are better than in the dry season because the dust and sand from Harmattan winds have diminished. In-flight visibilities, however, may still be restricted by suspended dust. Visibilities are lowest in the early morning due to fog and precipitation (see Figure 4-13). Squall-line precipitation occasionally reduces visibility to less than 1,000 meters.

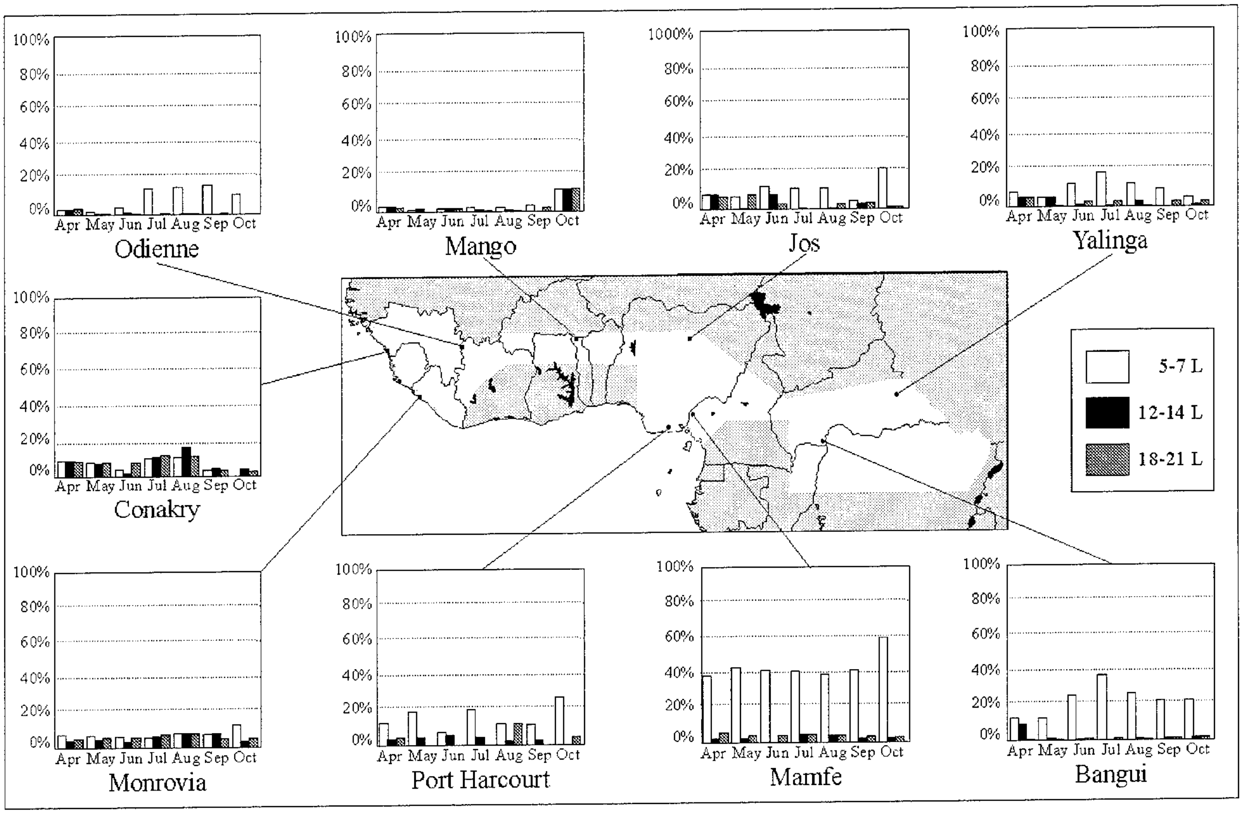


Figure 4-13. Wet-Season Percent Frequencies of Visibilities Below 4,800 meters.

Surface Winds. Surface winds are southwesterly at all locations (see Figure 4-14). Speeds are less than 17 knots, but they can reach 27 knots occasionally in coastal locations. The sea breeze, which reinforces the prevailing winds, is strongest from June through August.

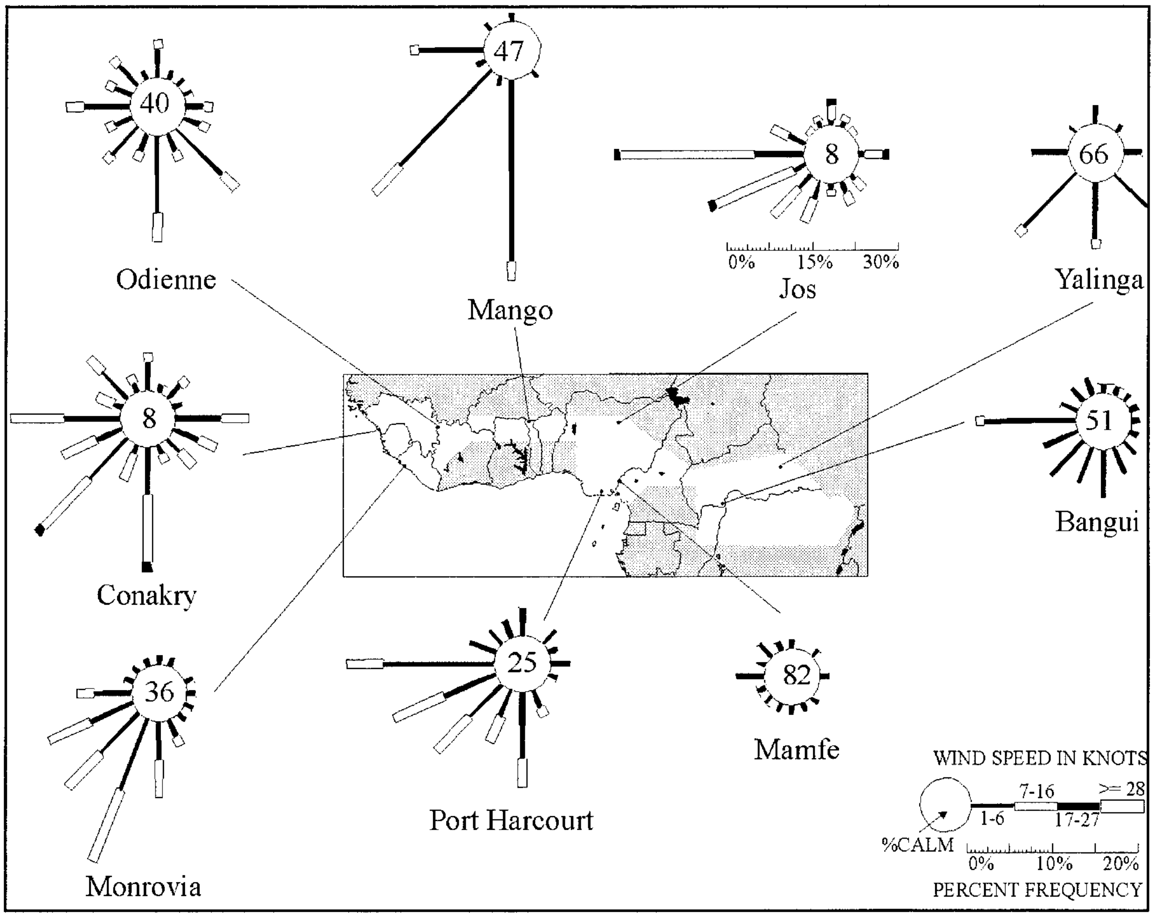


Figure 4-14. July Mean Surface Wind Roses.

Winds Aloft. Figure 4-15 shows the April, July, and October winds aloft at Bangui. The 850-mb winds are southerly in April, becoming southwesterly to westerly in July. They become northeasterly at up to 30 knots in October, signaling the end of the wet season. The MTEJ and TEJ are evident at 500 mb (easterly at up to 40 knots, occasionally 60 knots), and at 300 mb (up to 50 knots, occasionally 75 knots).

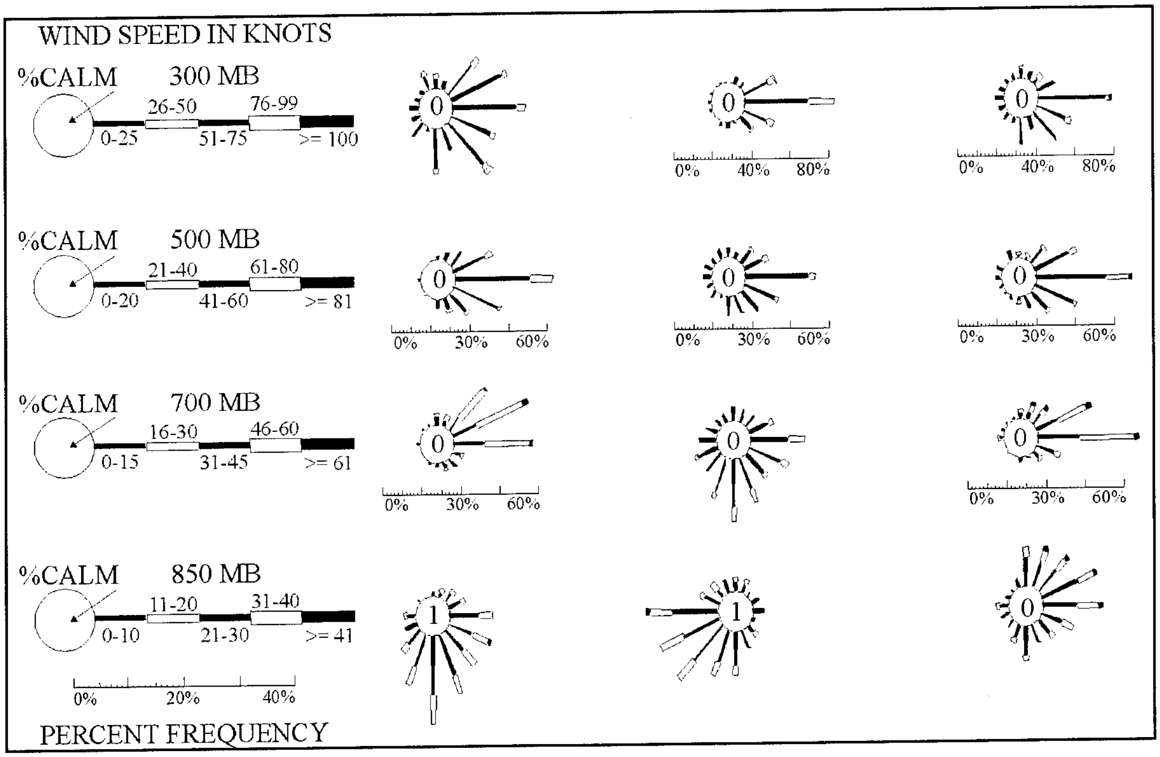


Figure 4-15. April, July, and October Mean Upper-Air Wind Roses at Bangui, Central African Republic.

Precipitation. The major moisture sources for rainfall are the Gulf of Guinea, the Atlantic Ocean, and the Congo Basin. Rainfall from the moist, maritime tropical air mass has several causes:

· *Orographic/relief rainfall* in the Cameroon Mountains, the coastal ranges, the Jos Plateau, and the Fouta Djallon Mountains.

· *Large-scale convergence* from July through September in west Africa south of 15° N. These monsoon rains are caused by the influence of the TEJ; convergence below the jet axis promotes widespread instability in the moist maritime tropical air mass. Widespread thick and continuous altocumulus and altostratus, as well as stratus and stratocumulus, cover west Africa from Cameroon to Sierra Leone (about 2,500 kilometers). The maximum of convergence-caused rainfall coincides with a period of minimum thunderstorm activity.

The wet-season precipitation maximum is usually in July or August (mean rainfall amounts for July are shown in Figure 4-16). Rainfall amounts are lowest near the equator and highest in the coastal regions, where rainfall averages 600-800 mm or more during July. Monrovia has more than 20 days a month with rainfall from July through September (see Figure 4-17). Other coastal locations see rainfall on 10-15 days of July and August.

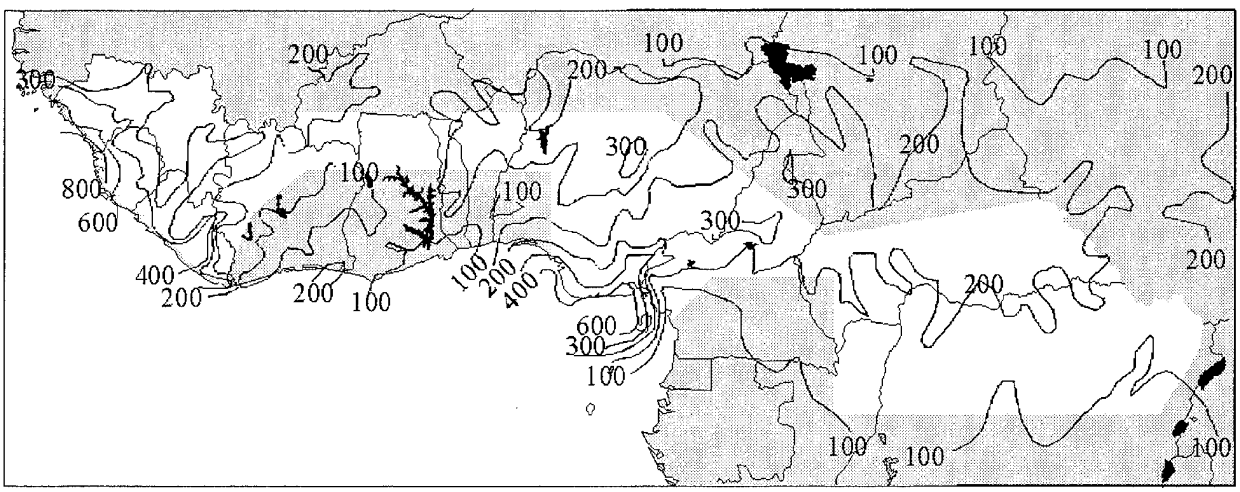


Figure 4-16. July Mean Precipitation (mm).

Thunderstorms. Thunderstorm days range from 10-15 days a month at many locations to as few as 5 at Jos (see Figure 4-17). Local convective thunderstorms are caused by intense solar heating, and occasionally by the heat from brush and forest fires. These storms last for 1 to 2 hours and cover 20-50 square kilometers.

African squall lines can be 300 to 500 kilometers long, oriented north to south and moving westward. As squall lines move through the area, surface winds back from southwest to southeast at about 30-35 knots, but stronger gusts are possible. Severe lightning and thunder accompany these squalls, and hail falls at higher elevations.

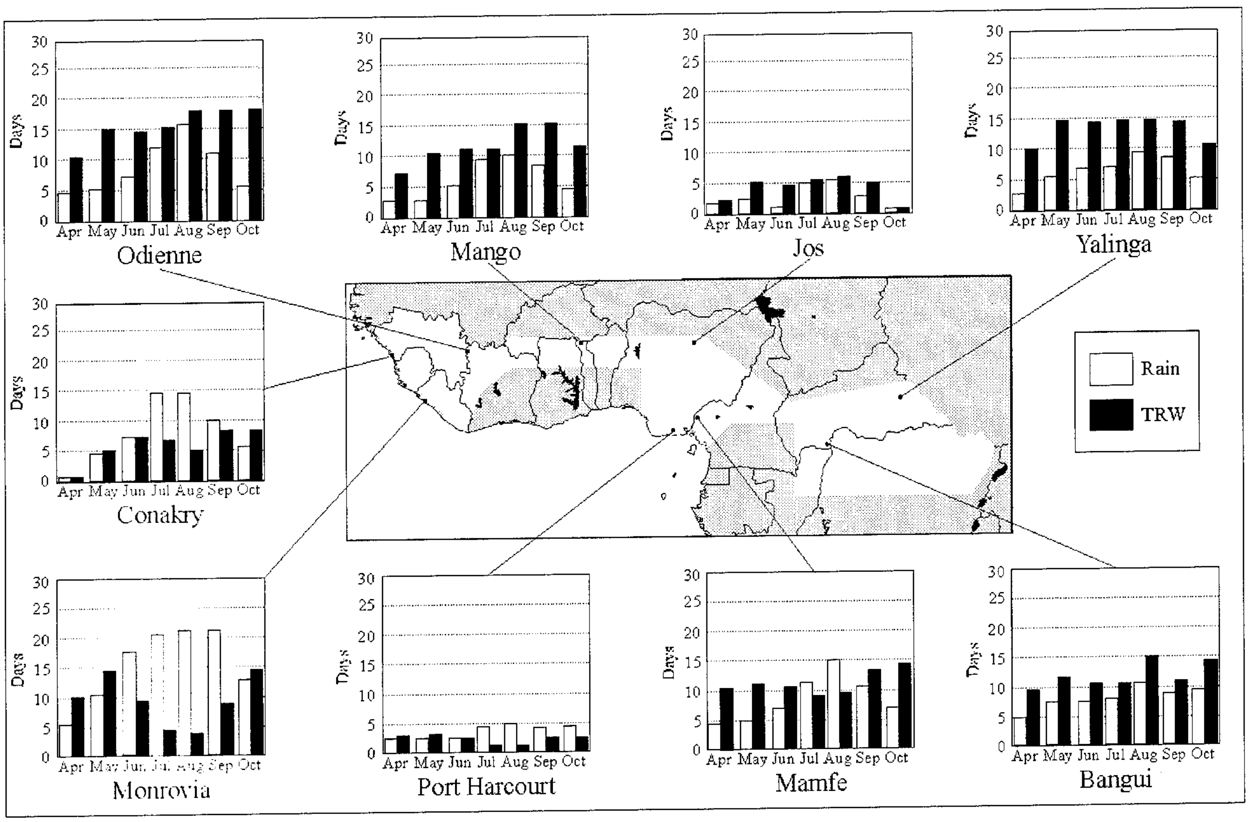


Figure 4-17. Wet-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Temperatures, although high, are more moderate than in the dry season due to the increased cloudiness and precipitation. Mean high temperatures in July vary from 30° C in northern parts of the zone to 26° C in the south. The lowest temperatures are usually in July or August. Mean low temperatures in July are near 21-23° C, but below 17° C at higher elevations. The lowest minimum temperatures are observed near the coasts.

Other Hazards. African Squall Lines are accompanied by severe lightning, strong gusty surface winds, low visibilities, and hail.

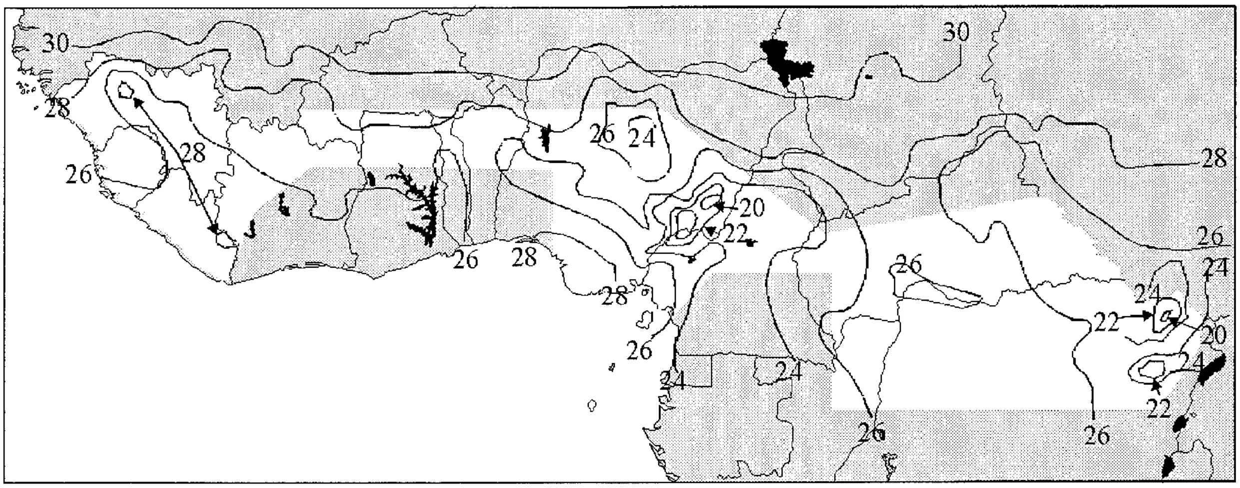


Figure 4-18. July Mean Maximum Temperatures (° C).

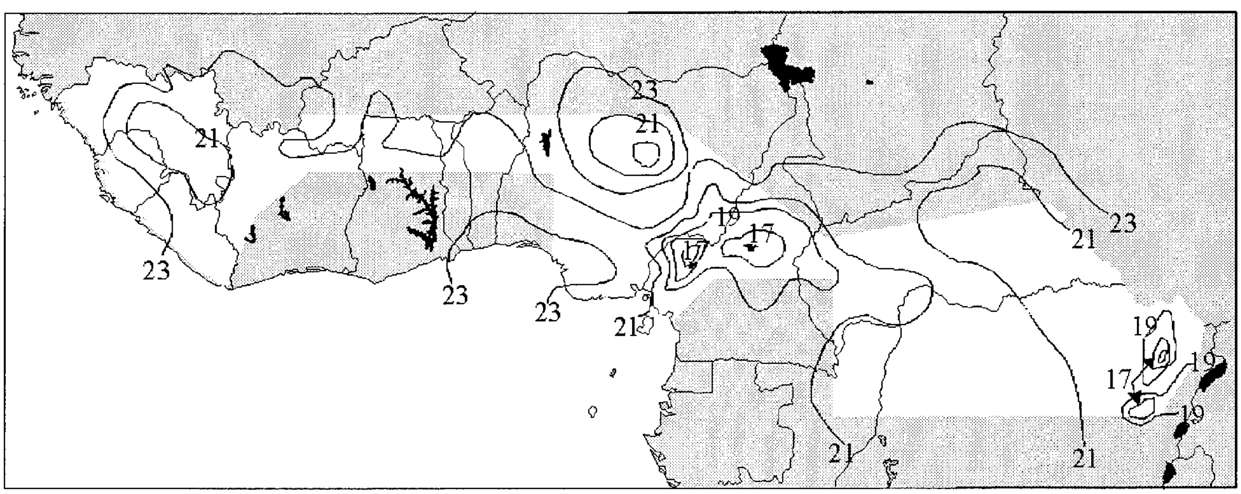
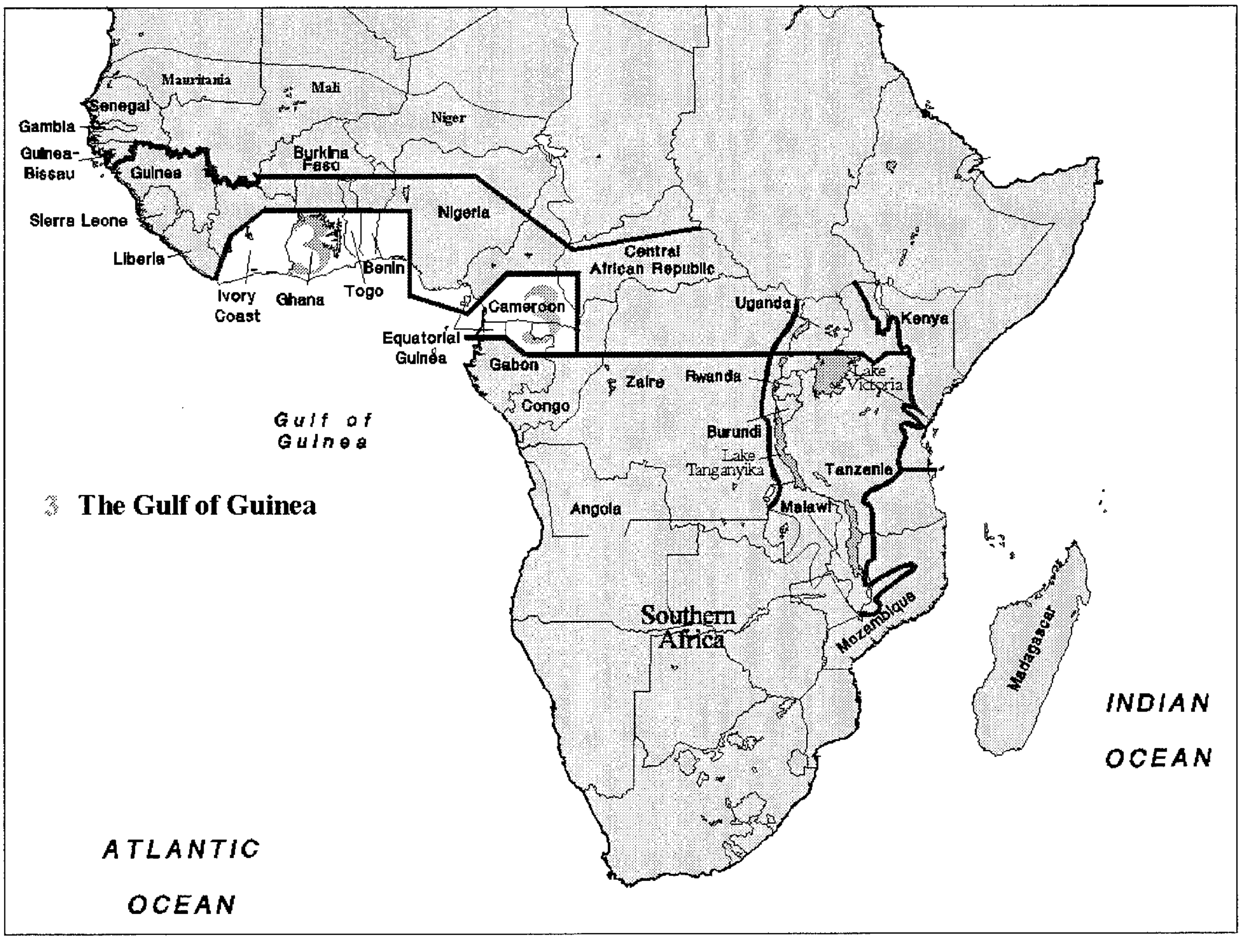


Figure 4-19. July Mean Minimum Temperatures (° C).

Chapter 5

THE GULF OF GUINEA

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) of that portion of Equatorial Africa known as the Gulf of Guinea. This "zone of climatic commonality" comprises two areas, both on the Gulf of Guinea but separated by a southward extension of the Northern Equatorial Belt. The westernmost part of this coastal zone includes parts of the Ivory Coast, Ghana, Togo, Benin and Nigeria. The eastern portion includes parts of Cameroon, the Central African Republic, Congo, Gabon, and all of Equatorial Guinea.



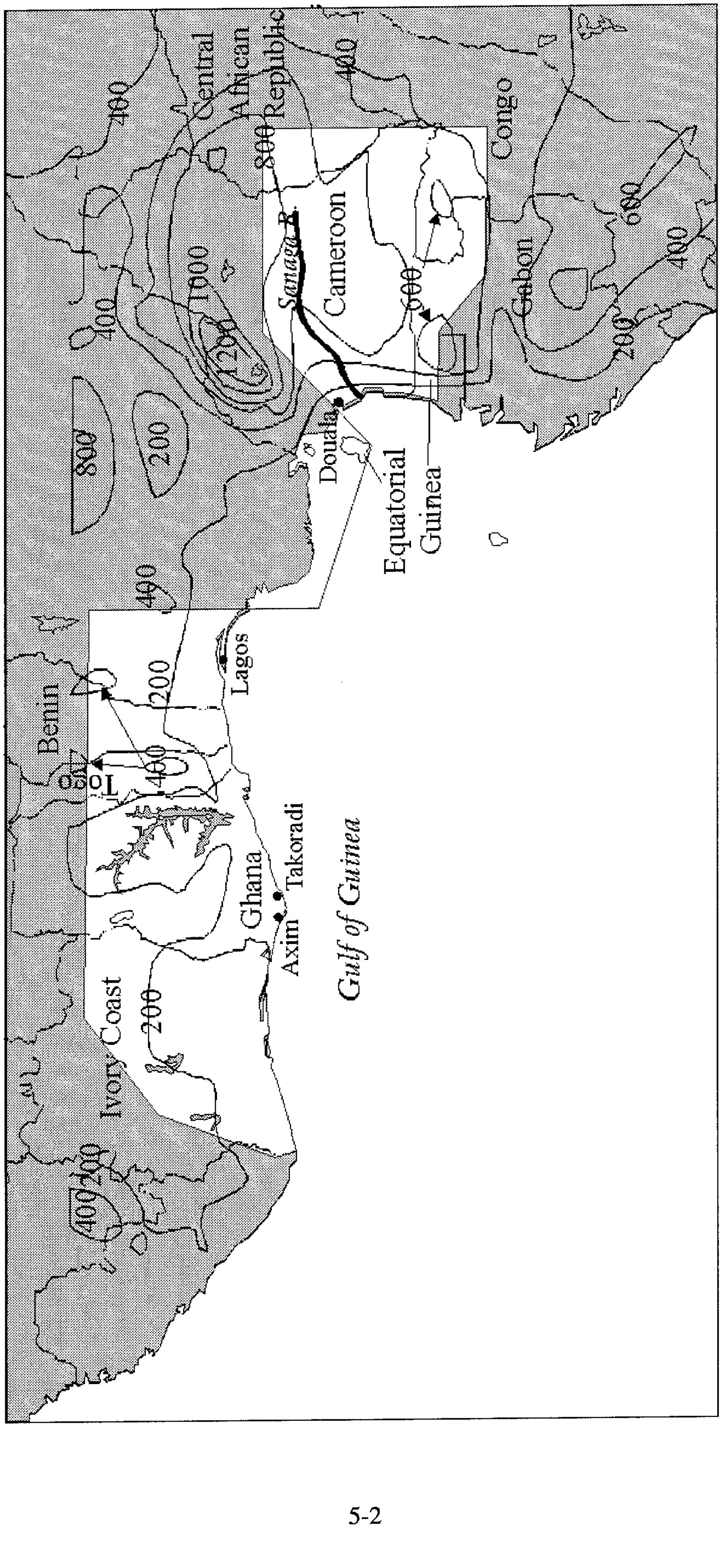


Figure 5-1. Topography of the Gulf of Guinea. Contours in meters.

Seasons. There are two "main" dry and wet seasons in this coastal zone, along with two "mini" dry and wet seasons. The main dry and wet seasons run from November to February and from March to June, respectively. The mini seasons run from July to August (dry) and from September to October (wet).

Boundaries. The Gulf of Guinea is an irregularly shaped, coastal climatic zone whose boundaries are drawn strictly by the limits of its dual wet and dry seasons. As shown in Figure 5-1, the zone is divided into two parts by a southward extension of the Northern Equatorial Belt. In the western portion, boundaries are drawn from the coast (near Tabou), north to 7° N and northeast to 8.5° N, 5° W; from there, east to 5° E, then south again to the coast. The eastern area starts at about 4° N, 9° E, goes northeast to about 5° N, 10° E, then east to 16 ° E and south to the equator. From there, the boundary goes west to 12° E, northwest to about 1° N, 11° E, and finally west to the coast.

Major Terrain Features. In the western portion of the zone, the coast is sandy, with many lagoons, sandbars, and some swamps. Along the Ivory Coast, the coastal area extends as far as 50 km inland. Beyond the coast, areas of extensive forests rise to over 400 meters east of Lake Volta. Southwest Nigeria has high plains and broad, shallow valleys. Cameroon's southern region contains coastal plains with densely forested plateaus; average elevations are about 300 meters. Equatorial Guinea's landscape is similar, except for its swampy coastline; the rest of the country rapidly changes to hilly terrain with elevations over 1,200 meters.

Rivers and Drainage Systems. Many small rivers originate in the inland hills and flow directly to the Gulf of Guinea. The Volta, with its main drainage source in Ghana, is the largest of these; its basin covers two-thirds of Ghana. Lake Volta, created by the Akosombo Dam, is about 400 km long and covers about 3% of Ghana. In northwestern Ghana, the Bui Dam creates a reservoir on the Black Volta. The other major river is the Sanaga, which originates in the mountains of northern Cameroon and flows about 300 km to the Gulf of Guinea.

Vegetation. Mangrove swamps line the coasts. Savanna, a mixture of tall grass and shrubs, grows inland, turning into tropical rain forests that contain both evergreen and semideciduous tress such as mahogany, ebony, and obeche. Over 3,000 species of vegetation grow in the rain forests. Still farther inland, the rain forest becomes a drier, highland type, with smaller trees.

MAJOR CLIMATIC CONTROLS OF THE GULF OF GUINEA

The Gulf of Guinea is governed by two wet and dry seasons of 4 months each, and two "mini" wet and dry seasons of 2 months each. Seasons change abruptly. The onset and duration of the seasons (which varies from year to year) is controlled by the movement of the Near Equatorial Trough (NET) that separates the dry Saharan (tropical continental) air mass in the north from the moist South Atlantic (tropical maritime) air mass in the south. The NET moves north and south as the air masses strengthen and weaken, causing the two wet and two dry seasons. To the north of the NET, hot and dry northeasterlies known as the "Harmattan" prevail. To the south, the warm and moist southwesterlies of the Southwest Monsoon dominate.

SPECIAL CLIMATIC FEATURES OF THE GULF OF GUINEA

African (Easterly) Waves. These disturbances, originating east of the zone, can produce short, intense showers and thunderstorms. They occur primarily during the September-October mini wet season.

Harmattan/Harmattan Haze. The Harmattan is a dry northeasterly wind that occurs primarily during the November-February dry season. The Harmattan wind picks up dust from the Sahara; the suspended dust results in the Harmattan Haze. North of the NET, the haze reduces surface visibility; south of the NET, it reduces visibility aloft.

African (Tropical) Squall Lines are primarily March-June wet-season phenomena. These westward-moving lines of showers and thunderstorms can bring strong winds and heavy rains.

General Weather. Although the NET is at its southernmost position, it does not enter the western part of this zone. As a result, the entire western portion, along with the northernmost part of the eastern portion, is under the influence of a relatively dry and stable air mass, with little rainfall. The southeastern portion of the zone, where there is considerably more moisture available, receives significantly more rain. Even though drier air extends into the region from the north, air near the surface is still very moist, with relative humidities about 95%. A persistent inversion over the region at about 800 mb inhibits deep convection. Stratus often develops from the lifting of thick, early morning fog, but it turns into stratocumulus and fair-weather cumulus later in the day. Precipitation falls occasionally.

Sky Cover. Cloudiness is at its yearly minimum. Although the surface NET passes through the zone, the areas of maximum cloudiness are to the south and west, as shown in Figure 5-2. Primary cloud types are stratus and stratocumulus in the morning and cumulus in the afternoon. Stratus ceilings develop at 300-600 feet in areas of thick fog, normally at 0700-0800L. These ceilings lift rapidly and become stratocumulus with bases near 1,000 feet and tops at 2,000 feet. Cumulus bases are 2,000-3,000 feet with tops at 8,000-10,000 feet.

As Figure 5-3 shows, ceilings below 3,000 feet are most common during the morning and early afternoon. Low ceilings are much more common at Douala, Bitam, and Makokou, where fog and mist lift to form ceilings. Frequencies of ceilings below 1,000 feet at these stations are less than 25%, and as low as 10% at Douala. Ceilings during the afternoon and evening are probably due to showers and thunderstorms.

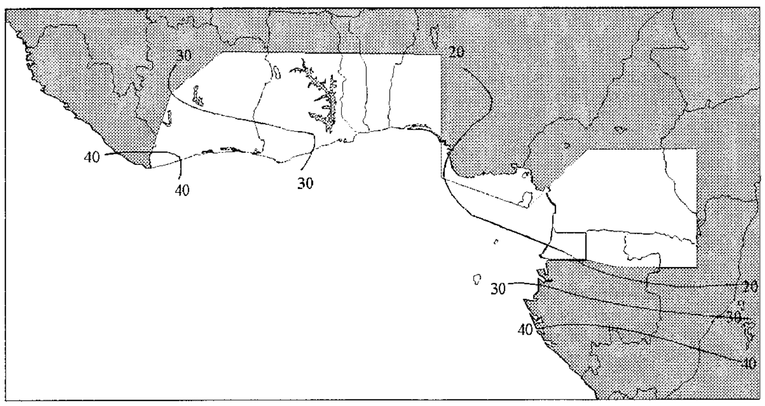


Figure 5-2. January Percent Frequencies of Ceilings.

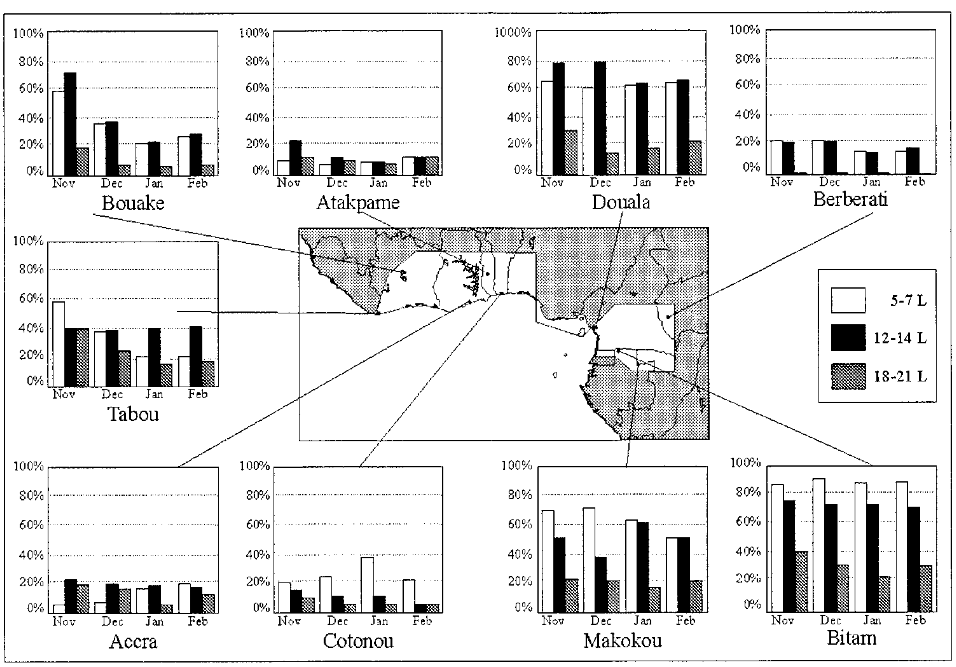


Figure 5-3. Dry-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. With the NET at its southernmost point, Harmattan haze is common both at the surface and aloft, but it is thicker and more frequent in the north; visibilities can be reduced to as low as 8,000 meters on the ground and 2,000 meters aloft. South of the NET, morning mist and fog are more likely to cause visibility restrictions. Visibilities improve considerably by mid-day except in the north, where Harmattan haze is most prevalent (Figure 5-4). Low visibilities at Bouake and Atakpame in the northwest are primarily due to haze. Cotonou, Tabou, and Accra have morning fog/mist and afternoon haze. Farther east and south, Douala has morning fog/mist and afternoon haze, while Berberati, Bitam, and Makokou have just morning fog/mist. Fog is most dense in the south, where early morning visibilities are below 1,600 meters 15-30% of the time at Cotonou, Douala, Bitam, and Berberati. Morning fog reduces visibility to less than 800 meters at Makokou more than 40% of the time.

As shown in Figure 5-4, the highest frequencies of visibilities below 4,800 meters are in December and January, when the NET is farthest south.

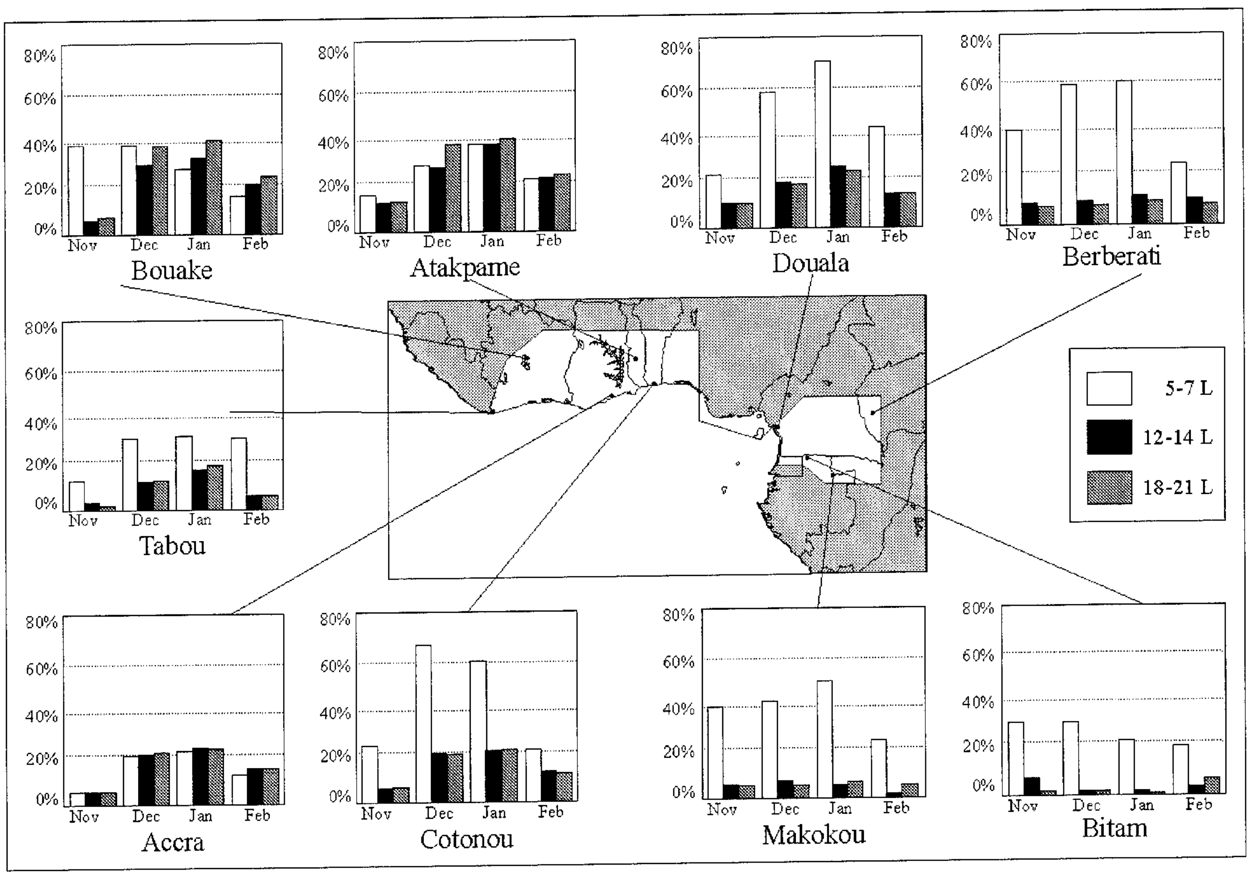


Figure 5-4. Dry-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. The winds are governed by NET position. The prevailing direction at a given location can change by 180 degrees in a day as a station comes under the influence of the Southwest Monsoon one day, but under the influence of the Harmattan the next. As seen in Figure 5-5, winds at Atakpame are primarily from the north (the Harmattan), while winds at Cotonou are primarily from the south (the Southwest Monsoon).

Winds are strongest in the afternoon when the thermal gradient is greatest (see Figure 5-6). Land/sea breeze circulations are weak. At night, winds tend to become calm, or light and westerly.

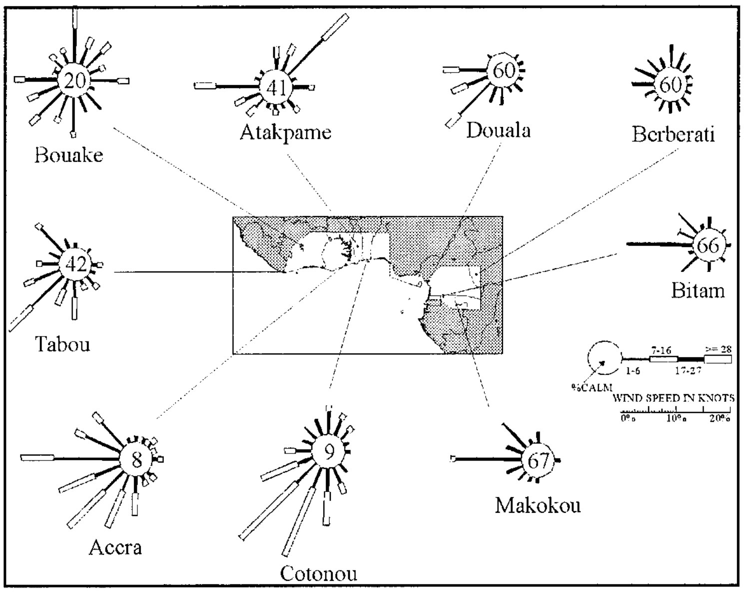


Figure 5-5. January Surface Wind Roses.

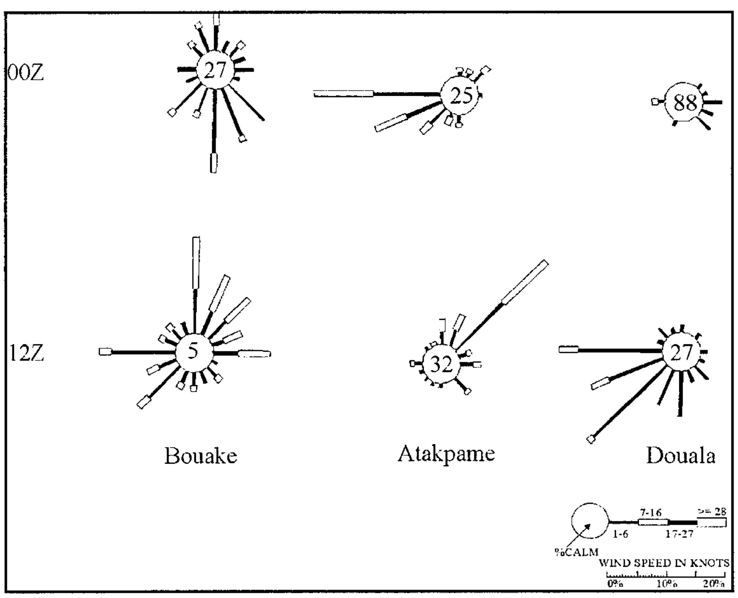


Figure 5-6. 00Z and 12Z Surface Wind Roses for January.

Precipitation. The onset of the main dry season depends on the position of the NET. In some areas, it may not begin until the middle of November. Dry-season precipitation is usually from brief showers or thunderstorms. As shown in Figure 5-7, precipitation is more common in the southeast, which is still south of the NET. Even though mean precipitation amounts in these coastal areas are close to 200 mm, this is actually a low for the year. As seen in Figure 5-8, the mean number of days with precipitation is greatest toward the beginning and end of the dry season.

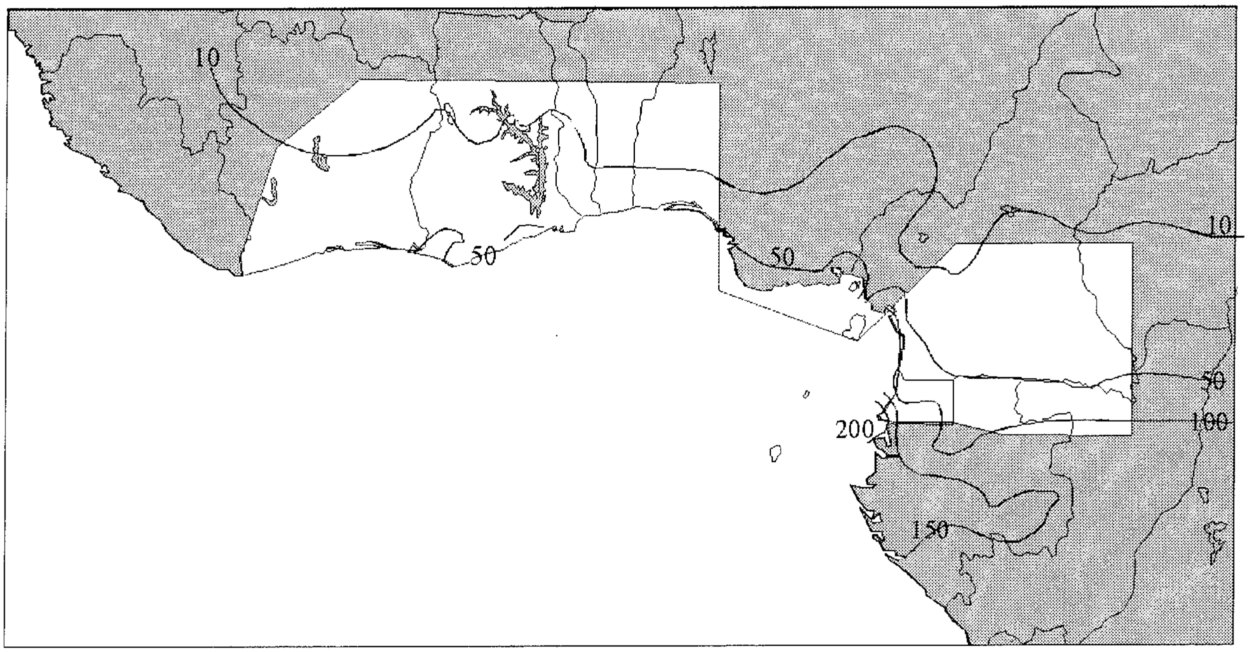


Figure 5-7. January Mean Precipitation (mm).

Thunderstorms are primarily of the isolated air-mass type. They most frequently form during the afternoon and evening, but most thunderstorms along the coastal part of the eastern area occur between midnight and 0600L. They are generally not severe. Bases can go as low as 200 feet, while tops can exceed 40,000 feet.

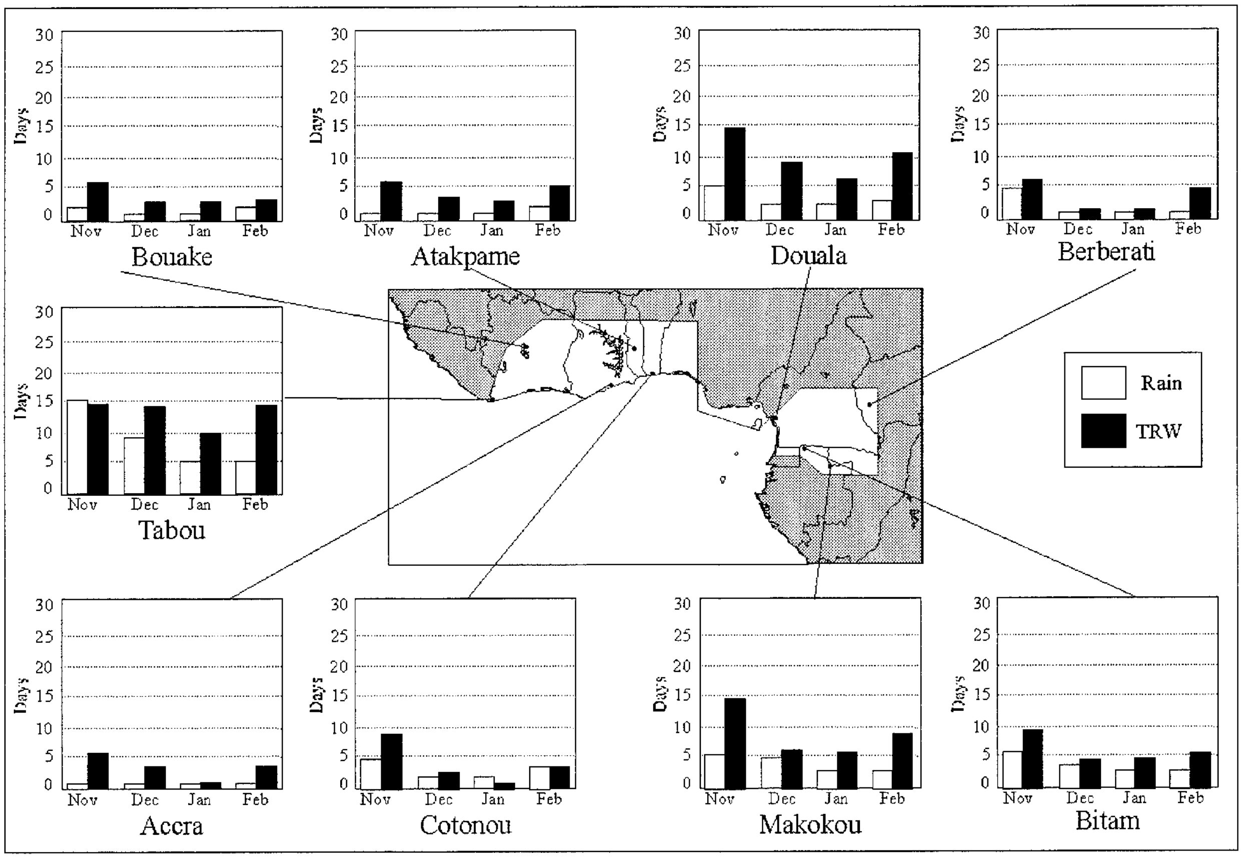


Figure 5-8. Dry-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Mean highs reach their annual peak in February or March. Mean annual lows are lowest in December or January. As Figures 5-9 and 5-10 show, highs are in the upper 20s to low 30s °C; lows are in the lower 20s °C. Extreme highs are in the upper 30s °C and extreme lows are in the upper teens. Extremes are most likely to occur north of the NET, where hot and dry air allows large diurnal variations. Average wet-bulb globe temperatures (WBGT) are around 30° C.

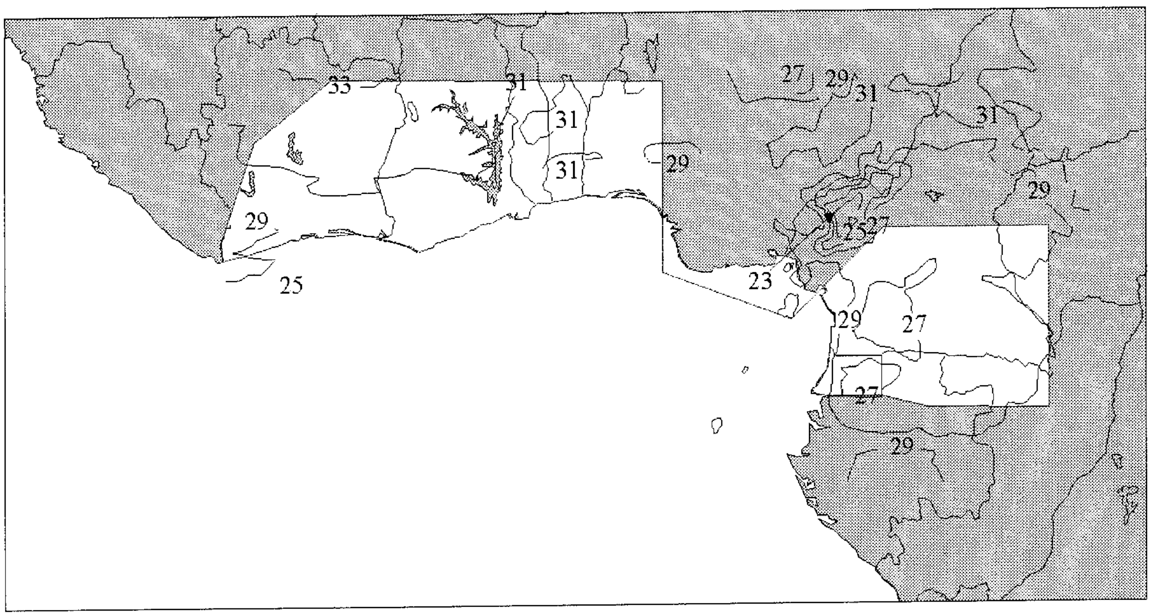


Figure 5-9. January Mean Maximum Temperatures (° C).

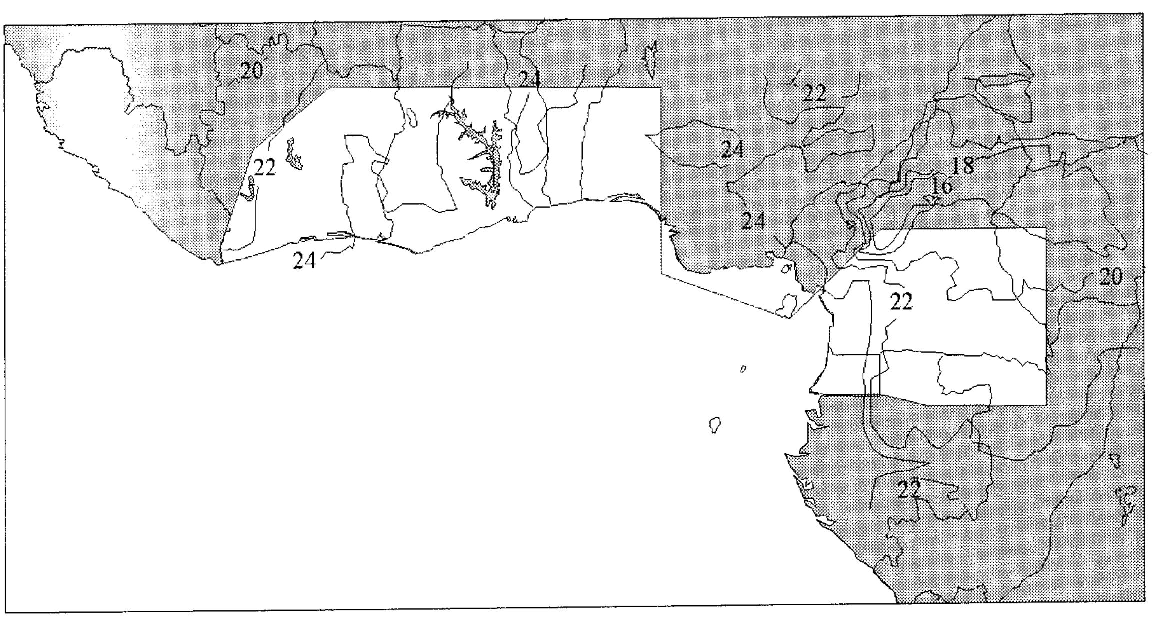


Figure 5-10. January Mean Minimum Temperatures (° C).

General Weather. The main wet season starts gradually, but ends suddenly. It begins as the NET begins its northward progression and as the African Easterly Jet and the Easterly Tropical Jet become established (see Chapter 2). The appearance of these jets coincides with the enhanced development of synoptic disturbances such as easterly waves and squall lines.

Sky Cover. As the NET moves north, sky cover increases and ceilings become more common (see Figure 5-11). The primary cloud is cumulus that develops into cumulonimbus. Squall lines produce afternoon showers and thunderstorms.

Morning scattered-to-broken stratocumulus is common, with bases at 1,000 to 1,300 feet. By 1000L, scattered-to-broken cumulus forms, with bases from 1,500-3,000 feet. By 1400L, scattered cumulonimbus develops; bases are as low as 200 feet and tops can exceed 50,000 feet. Fast-moving squall lines can bring in cumulonimbus ceilings as low as 200 feet, but they don't last long.

As Figure 5-12 shows, ceilings below 3,000 feet become more common throughout the season in most areas. Low ceilings are most common in the morning or afternoon. Morning temperatures quickly reach the convective temperature, allowing cumulus to develop. At Berberati, Bitam, and Makokou, fog lifting into stratus also contributes to low ceilings. Cloud cover decreases during the evening as showers or thunderstorms dissipate. Towering cumulus and cumulonimbus may also develop due to the intense heat generated by agricultural burning in the forest zone and brush fires in the grasslands.

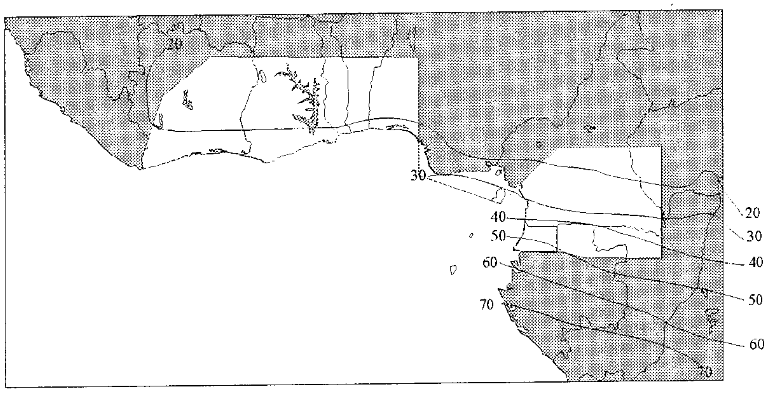


Figure 5-11. April Percent Frequencies of Ceilings.

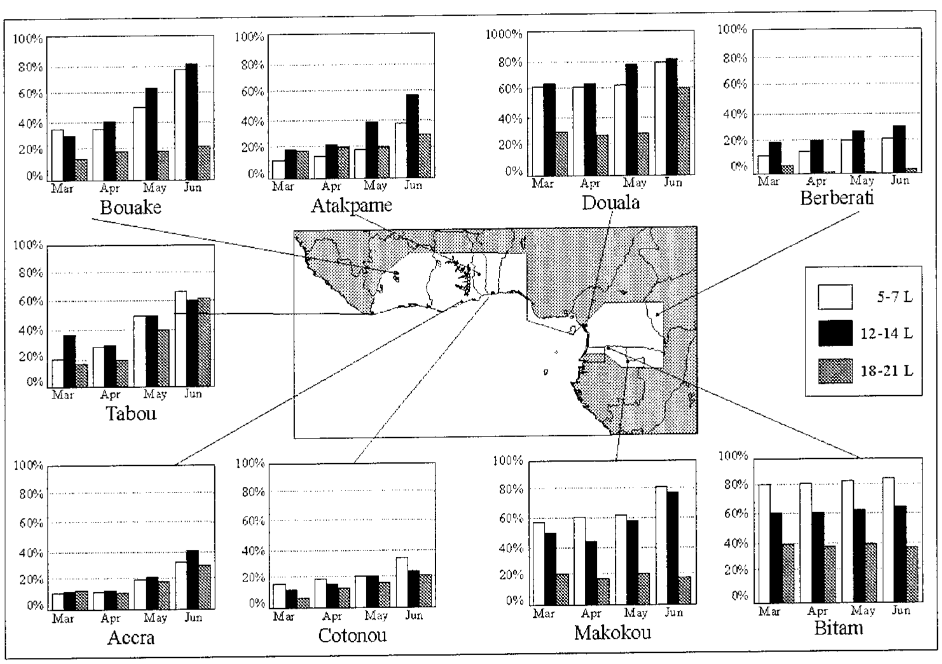


Figure 5-12. Wet-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Mist and fog cause most morning visibility restrictions. As shown in Figure 5-13, some areas have relatively high frequencies of low visibility. Showers and thunderstorms can cause restrictions during the morning, but they are more common in the afternoon and evening. Visibility sometimes goes to zero in showers, but usually only for a short time.

Fog causes most morning visibility restrictions at Berberati, Bitam, and Makokou, where visibility drops to less than 800 meters as much as 30% of the time. The fog lifts rapidly by mid-morning.

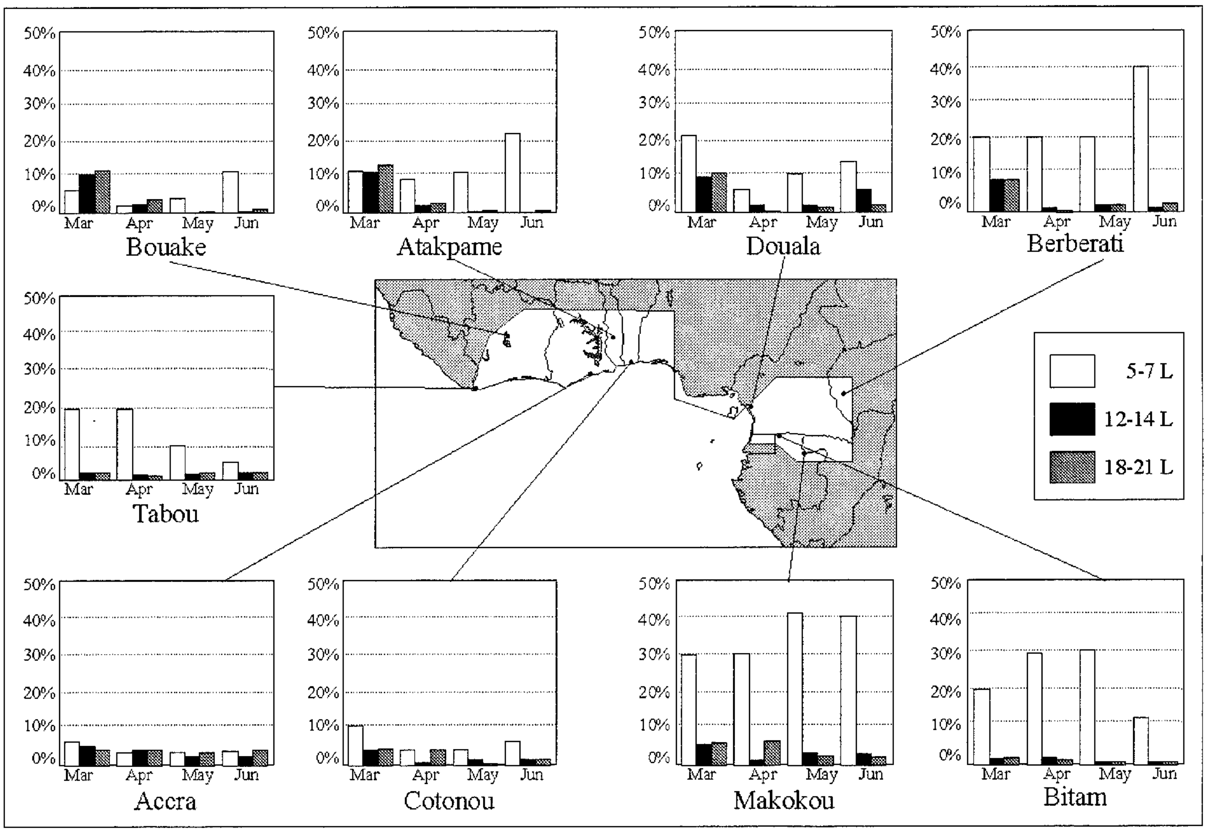


Figure 5-13. Wet-Season Frequencies of Visibilities Below 4,800 meters.

Winds. Southwesterly winds prevail (see Figure 5-14). Winds are lighter in the east due to the sheltering effects of terrain. Winds are strongest in the afternoon (see Figure 5-15) when the thermal gradient is greatest. A weak land breeze may form at night. Strong easterly or northeasterly winds accompany squall lines. Gusts are usually 25-30 knots, but they can be as high as 40-45 knots.

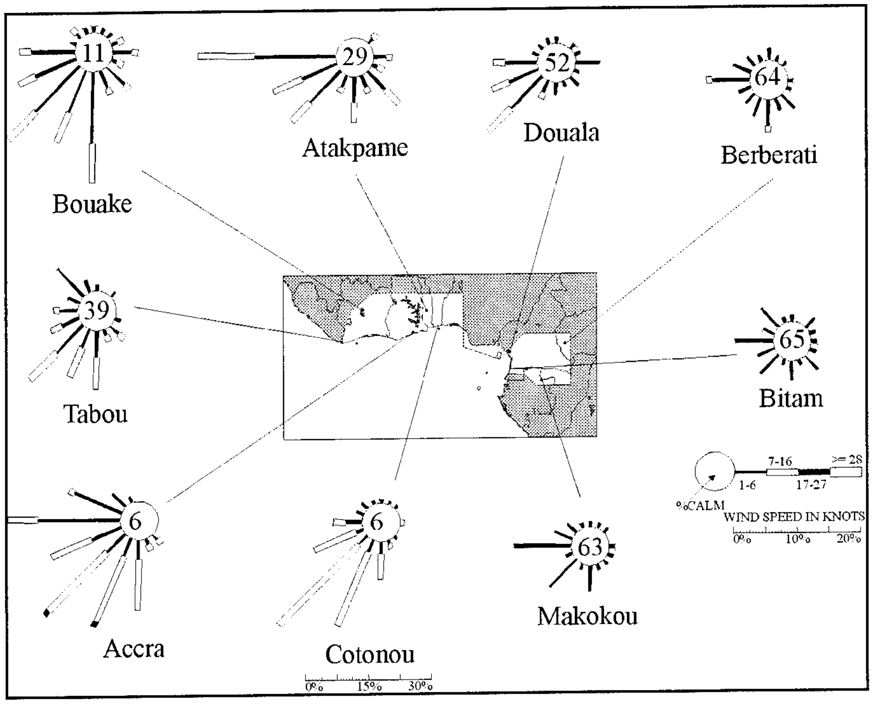


Figure 5-14. April Surface Wind Roses.

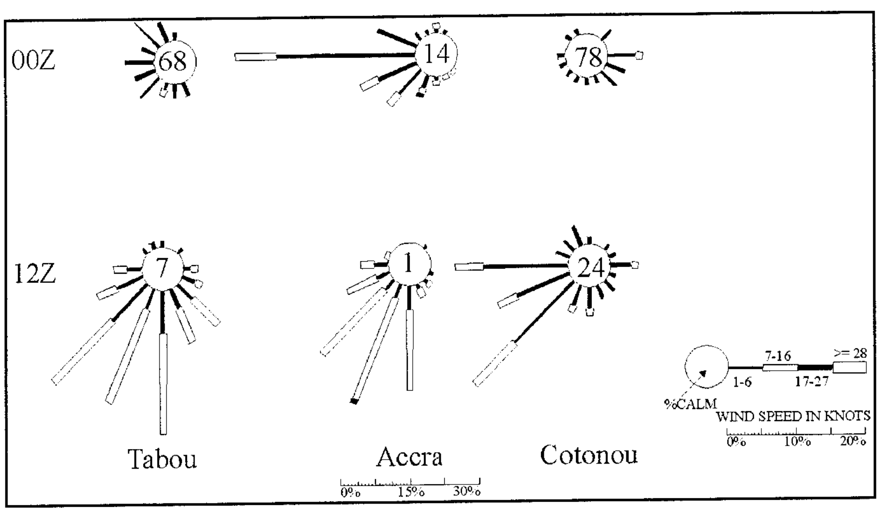


Figure 5-15. 00Z and 12Z Surface Wind Roses for April.

Precipitation. Early in the season, afternoon and evening air-mass rainshowers and thunderstorms develop frequently. As the season progresses, showers and thunderstorms may occur at any time of day or night. Squall lines also begin to appear with increasing frequency. They are most common in May, when they occur on about 1 day in 3. In June, thunderstorms decrease appreciably in intensity, giving way to light but persistent monsoon rains that last up to 12 hours. At Lagos, squall lines contribute an estimated 60% of the rainfall in March, but only 3% in June.

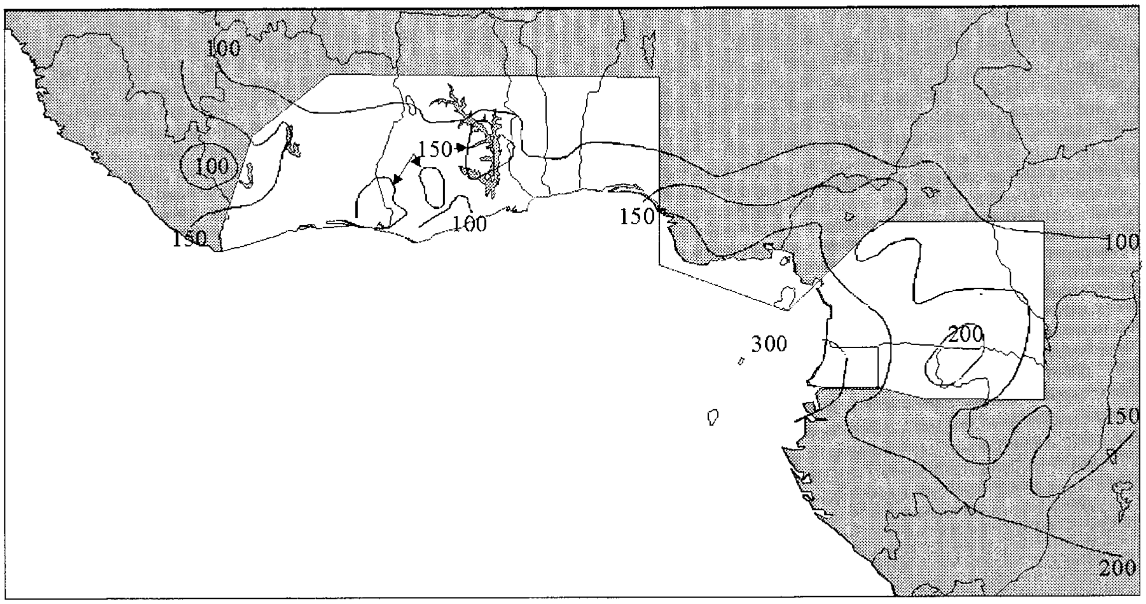


Figure 5-16. April Mean Precipitation (mm).

Thunderstorms. Most severe storms are associated with squall lines. Cloud bases can be as low as 200 feet and tops can exceed 50,000 feet. Zero visibilities and flash flooding may result from these storms. African squall lines are normally fast-moving, reducing ceilings and visibility for only short periods. After the monsoon has begun, thunderstorm activity decreases considerably, and monsoonal rains begin. This is evident in Figure 5-17, which shows mean thunderstorm days decreasing in June for most areas.

Tropical waves are also important in controlling convection. Their passage is closely linked to increases in convection amount and intensity. The most vigorous convection is observed ahead of the 700-mb trough, followed by minimal convective activity a day after trough passage.

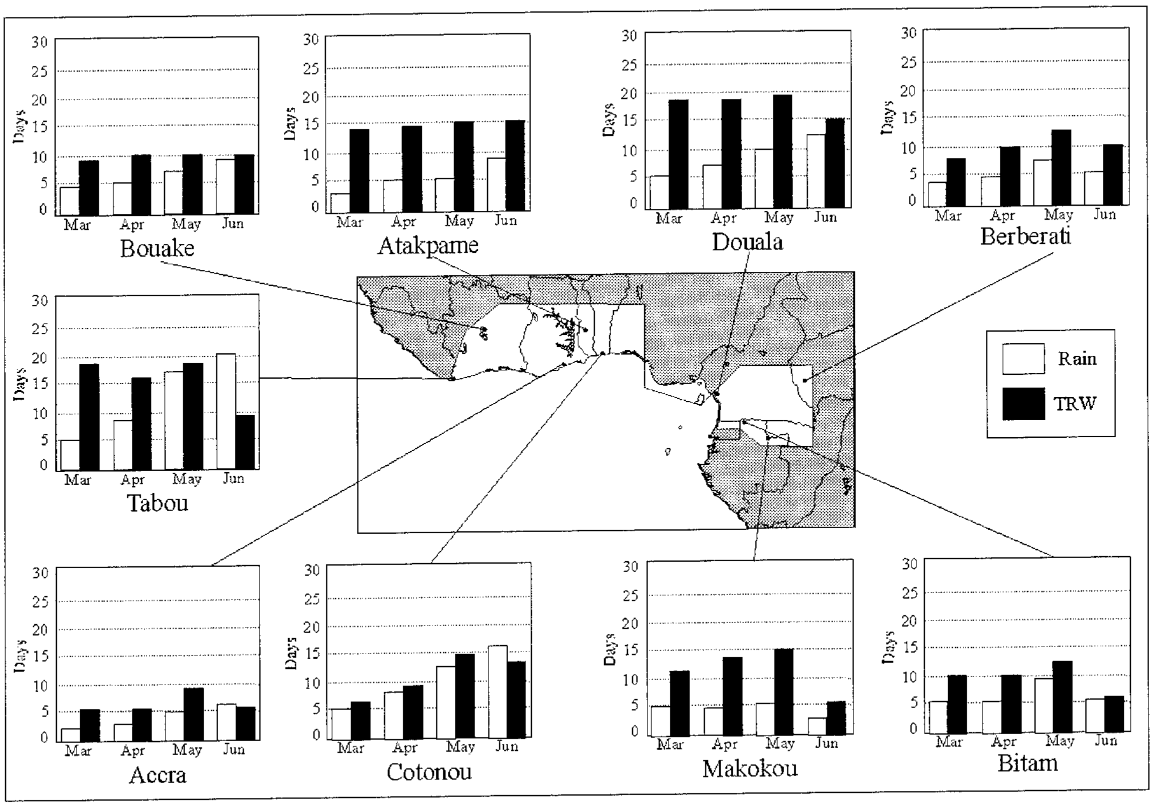


Figure 5-17. Wet-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. As shown in Figures 5-18 and 5-19, there is very little diurnal variation between mean highs and lows. Extreme highs are in the upper 30s °C, while extreme lows are in the upper teens. Humidities are very high. Average WBGTs are around 30° C.

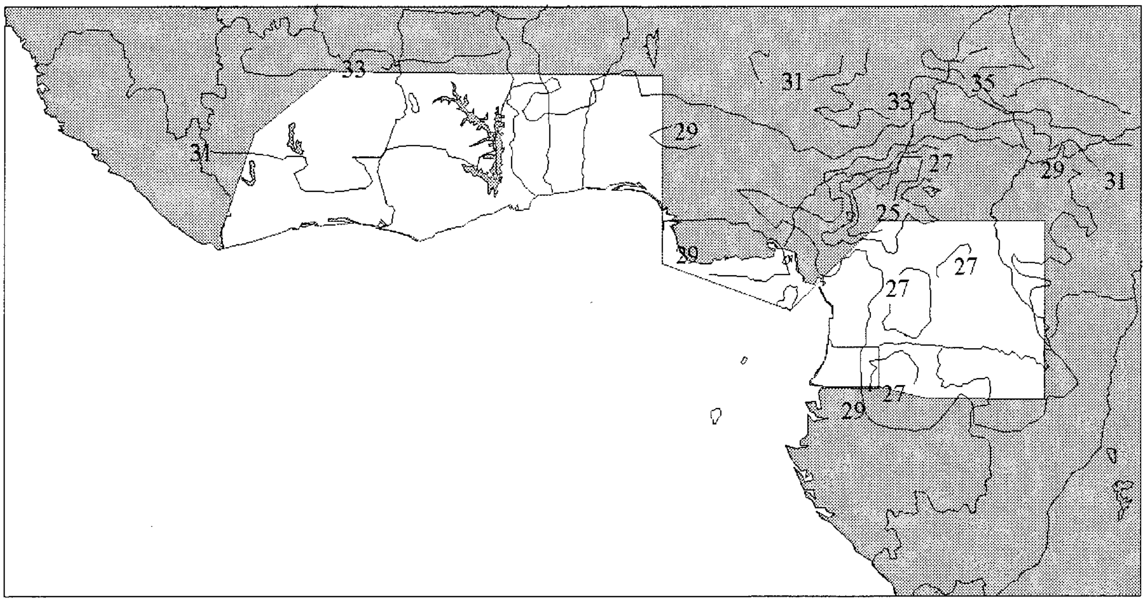


Figure 5-18. April Mean Maximum Temperatures (° C).

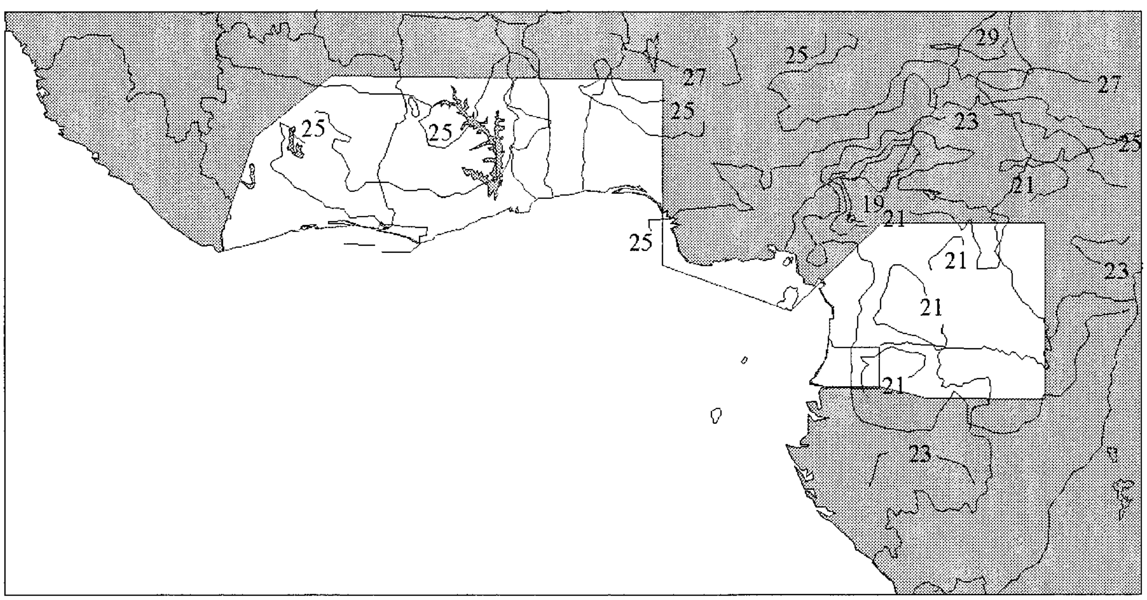


Figure 5-19. April Mean Minimum Temperatures (° C).

General Weather. The NET reaches its northernmost point during this secondary dry season, causing the area of maximum rainfall to move north, as well. However, moist southwesterly winds, combined with topography, can still cause considerable precipitation in the eastern part of the zone.

Sky Cover. Surface air is very moist (95% relative humidity), but a persistent inversion near 800 mb inhibits deep convection. Some areas often have a layer of stratus with bases below 500 feet from the lifting of morning fog. The stratus breaks and lifts into stratocumulus with bases at 1,000-2,000 feet. Fair-weather cumulus with bases from 2,500-3,500 feet forms later in the day.

As shown in Figures 5-20 and 5-21, ceilings are most common in the eastern part of the zone, where the weaker inversion allows for more cloud development and more precipitation. Early morning and afternoon ceilings are caused either by stratocumulus advected into the area (as is the case for Accra, Cotonou, Tabou, Bouake, and Bitam), or by fog lifting into stratus (as is the case with Atakpame, Berberati, and Makokou). Ceilings at Berberati, Atakpame, and Makokou fall below 500 feet as much as 25% of the time. Ceilings rarely fall below 1,000 feet at Accra, Cotonou, and Tabou. At Douala, high low-ceiling frequencies are caused by showers or thunderstorms.

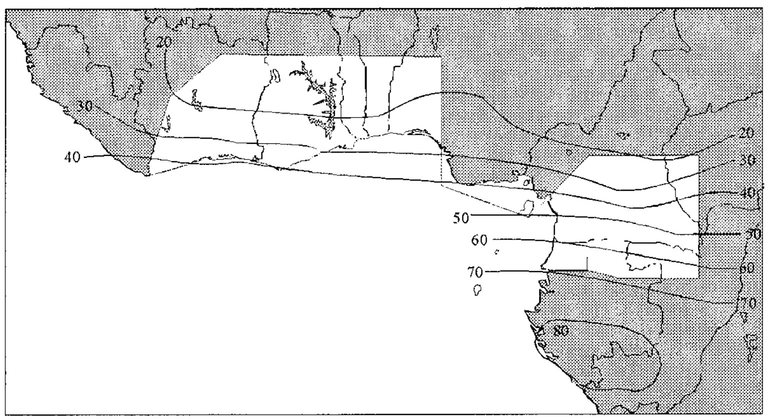


Figure 5-20. July Percent Frequencies of Ceilings.

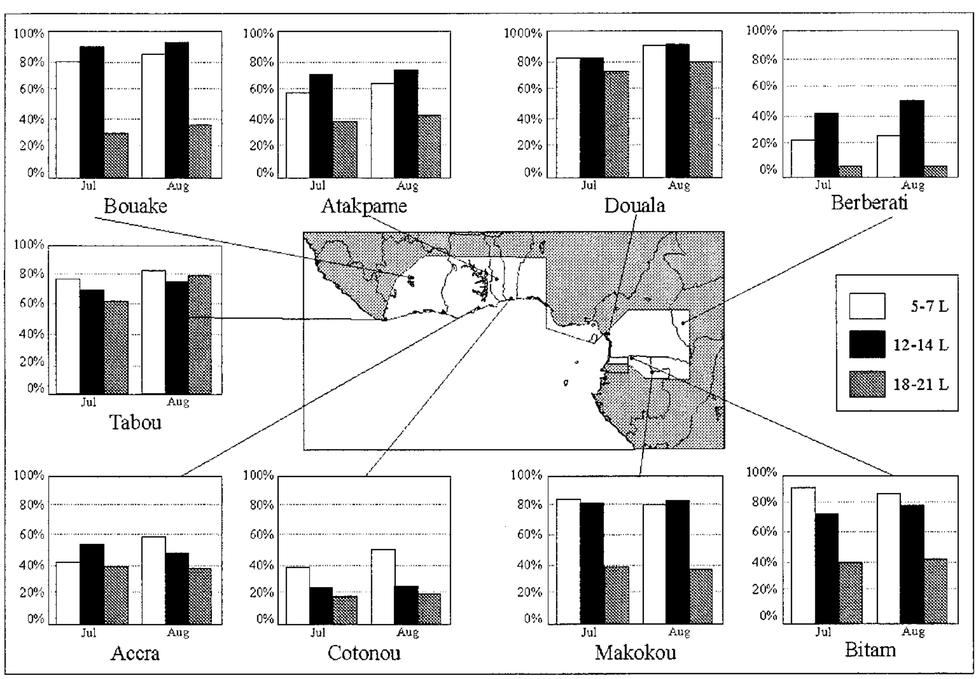


Figure 5-21. Mini Dry Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Fog causes most visibility restrictions. Only at Douala does precipitation play a significant role. As seen in Figure 5-22, the highest frequency of visibilities below 4,800 meters is in the morning. By afternoon, the fog lifts or burns off. Visibility is below 800 meters almost 50% of the time in Atakpame and about 25% of the time in Makokou; visibility at both stations improves rapidly after 0700L.

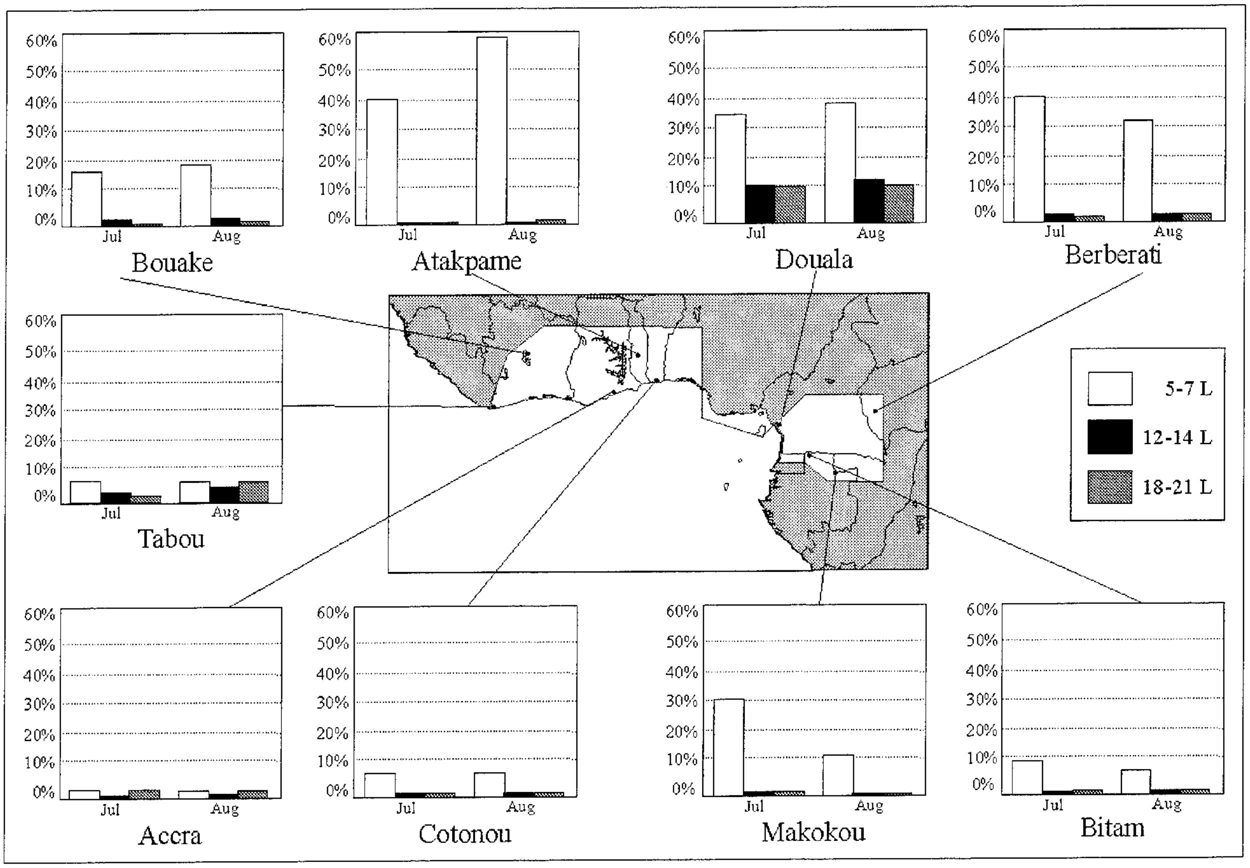


Figure 5-22. Mini Dry Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. Southwesterly winds prevail in the western part of the zone, while winds in the eastern part are westerly (see Figure 5-23). The Tropical Easterly Jet flows directly over the region. Winds are stronger during the afternoon (see Figure 5-24), when thunderstorms often bring gusty winds. Westerly winds bring Douala and the surrounding coastal areas moisture for the enhanced precipitation that is shown in Figure 5-25.

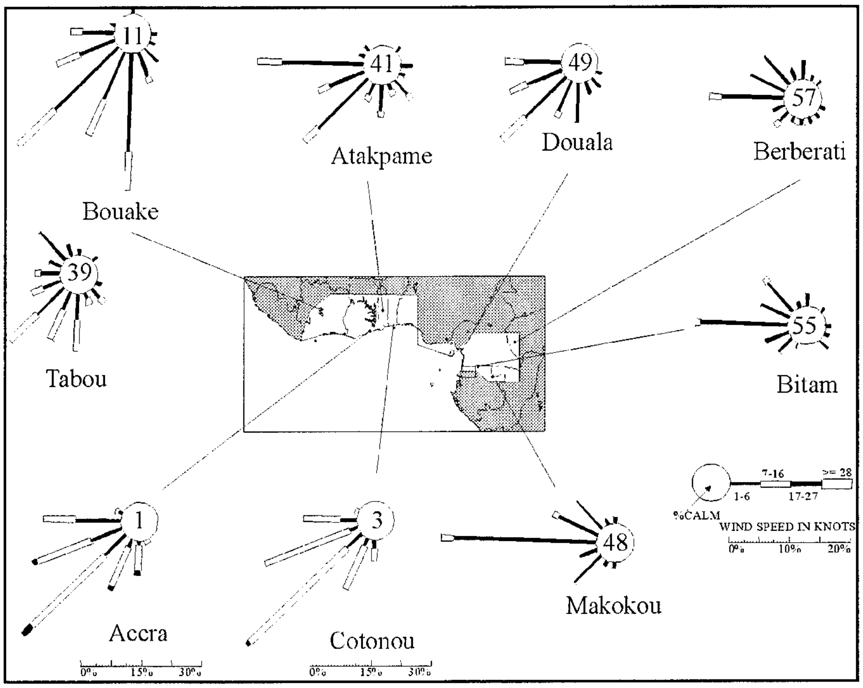


Figure 5-23. August Surface Wind Roses.

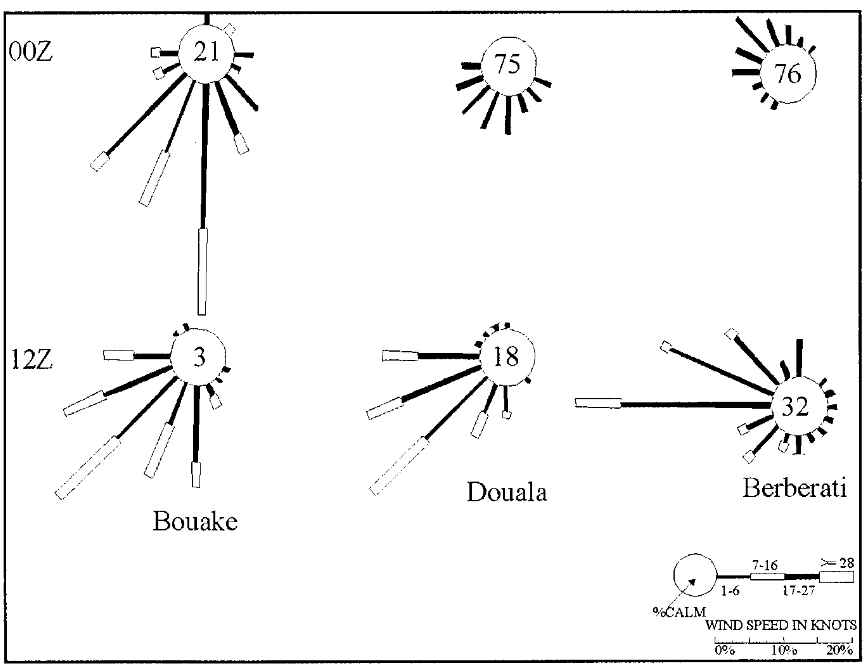


Figure 5-24. 00Z and 12Z Surface Wind Roses for August.

Precipitation. Most of the western part of the zone is very dry, especially near the coast. This is due to the temperature inversion that inhibits convective activity and rainfall. Any precipitation along the coast is usually in the form of light drizzle. Farther inland, a few air-mass showers form with afternoon heating.

Over the eastern part of the zone, southwesterly and westerly flows converge. With the help of terrain, this convergence enhances rainfall and produces the precipitation pattern shown in Figure 5-25. This effect is especially noticeable around Douala.

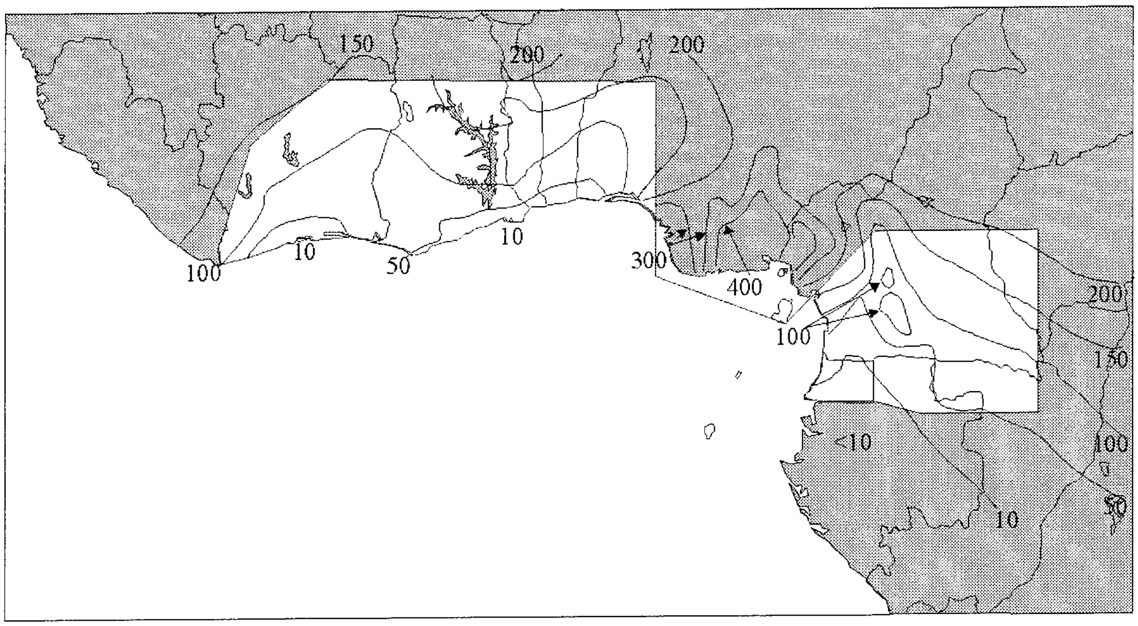


Figure 5-25. August Mean Precipitation (mm).

Thunderstorms are mainly confined to the afternoon, over inland areas. This is evident in Figure 5-26, which shows only two stations with more thunderstorm days than rain days. Thunderstorm bases can be as low as 200 feet in showers, while tops are around 40,000 feet.

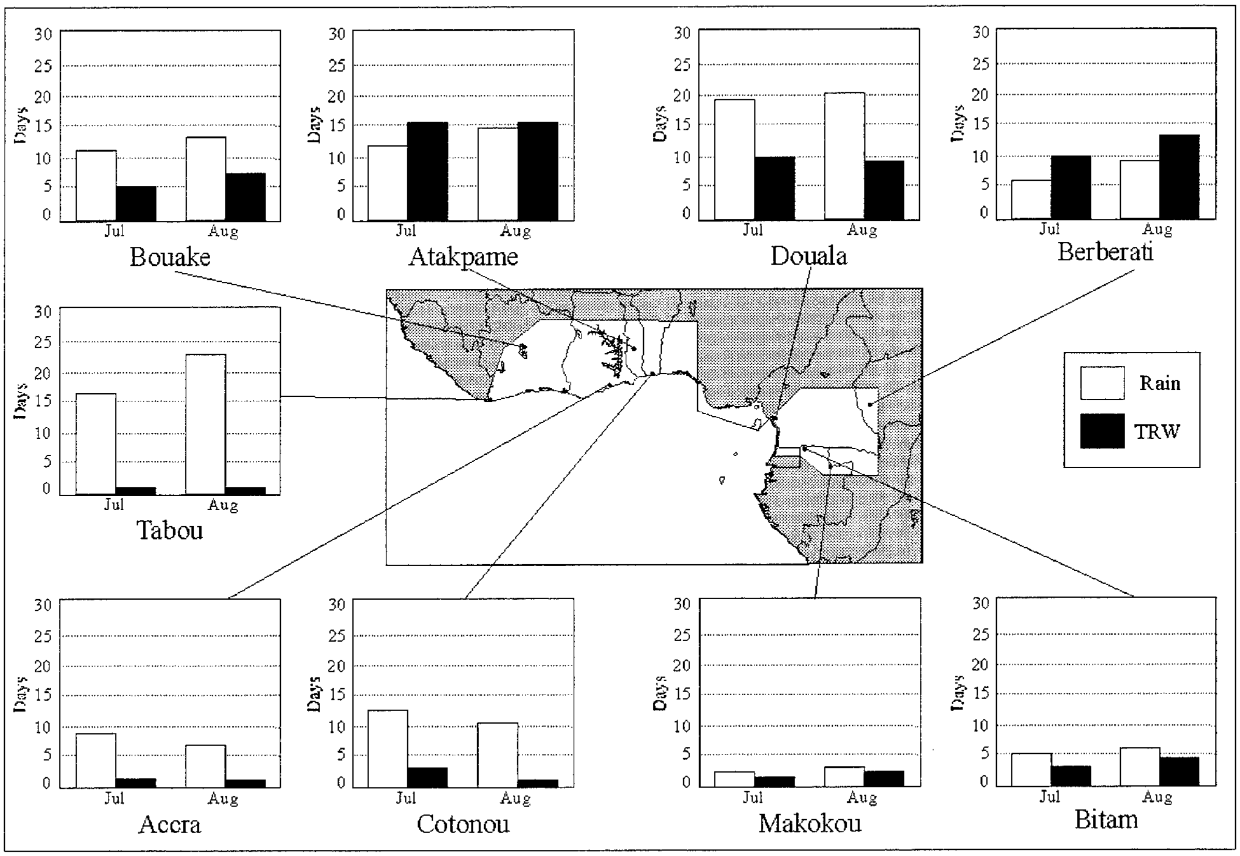


Figure 5-26. Mini Dry Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. As shown in Figures 5-27 and 5-28, there is a difference of about 4 Celsius degrees between mean highs and lows. Extreme highs are in the low to mid 30s °C and extreme lows are in the low to mid teens. July WBGTs are 28-30° C.

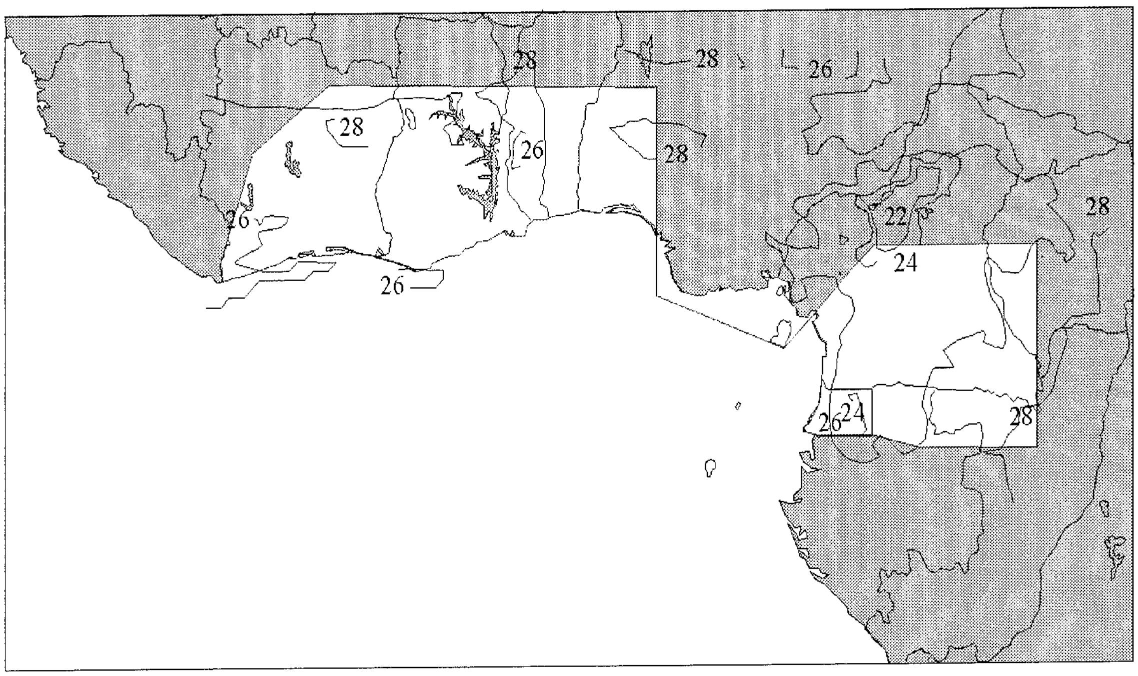


Figure 5-27. August Mean Maximum Temperatures (° C).

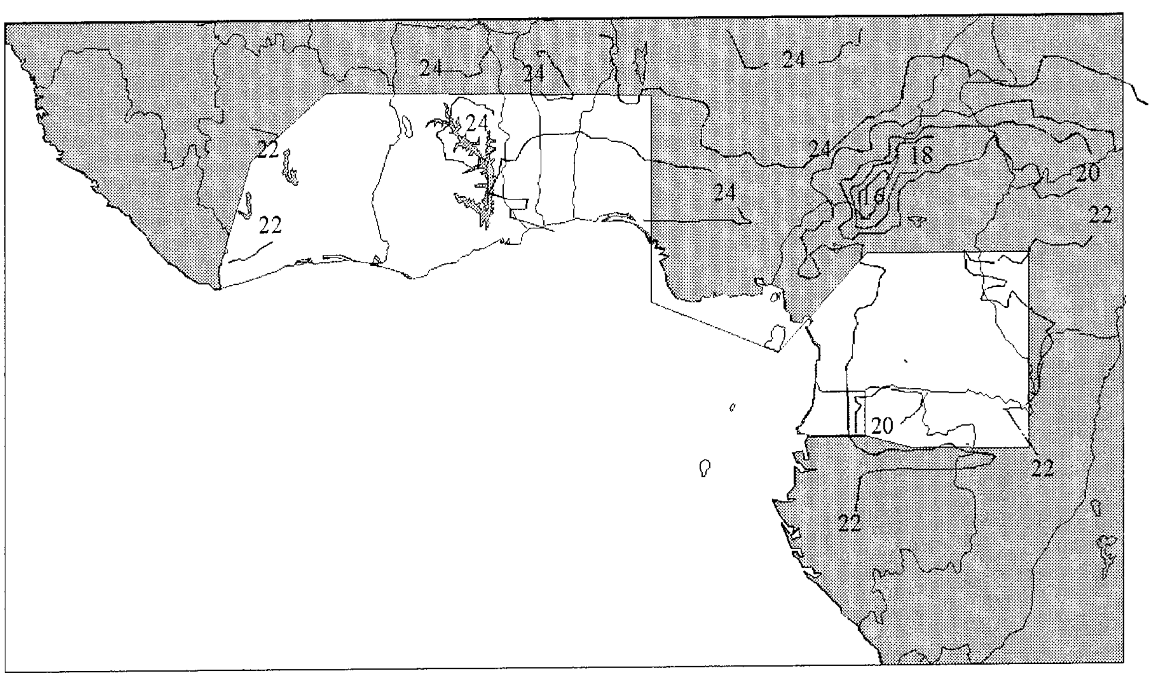


Figure 5-28. August Mean Minimum Temperatures (° C).

General Weather. The NET begins moving south, bringing the zone under the influence of a moist and unstable air mass. Beginning and ending dates of this season can vary by as much as 15 days. The beginning of the rains coincides with the appearance of the Mid-Tropospheric Easterly Jet. In some years, when the NET moves south rapidly, this season almost goes unnoticed.

Sky Cover. Most morning clouds are stratocumulus. In the few areas that have fog, stratus is more prevalent. As the morning progresses, both cloud types lift; cumulus develops, with bases at 2,000 to 3,000 feet and tops from 10,000 to 20,000 feet.

As seen in Figure 5-29, ceiling frequencies are actually less than those in July (the mini dry season), possibly because the moisture-capping inversion is not present in the mini wet season. Low ceilings (Figure 5-30) are most common in the morning and early afternoon. Stratus ceilings are often below 500 feet, but they lift rapidly into stratocumulus and cumulus by early morning. Stations with morning stratus are Bouake, Atakpame, Bitam, and Berberati.

Some stations, such as Tabou, Douala, and Makokou, see frequent low ceilings in the morning from showers and thunderstorms. Squall lines begin to occur more often, lowering ceilings to below 500 feet for short periods.

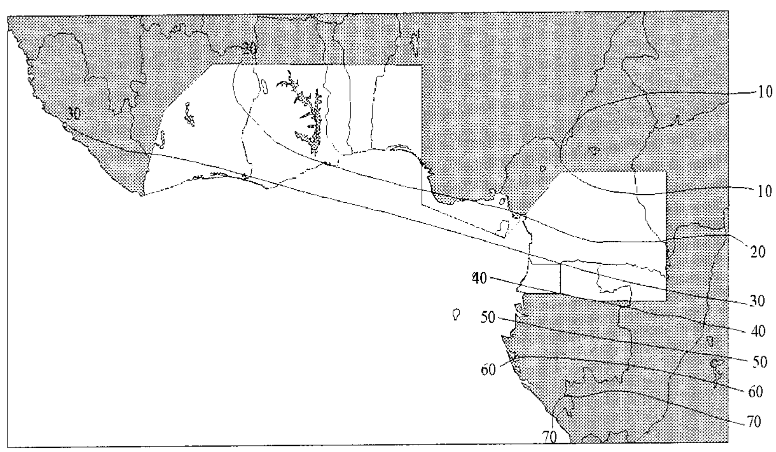


Figure 5-29. October Percent Frequencies of Ceilings.

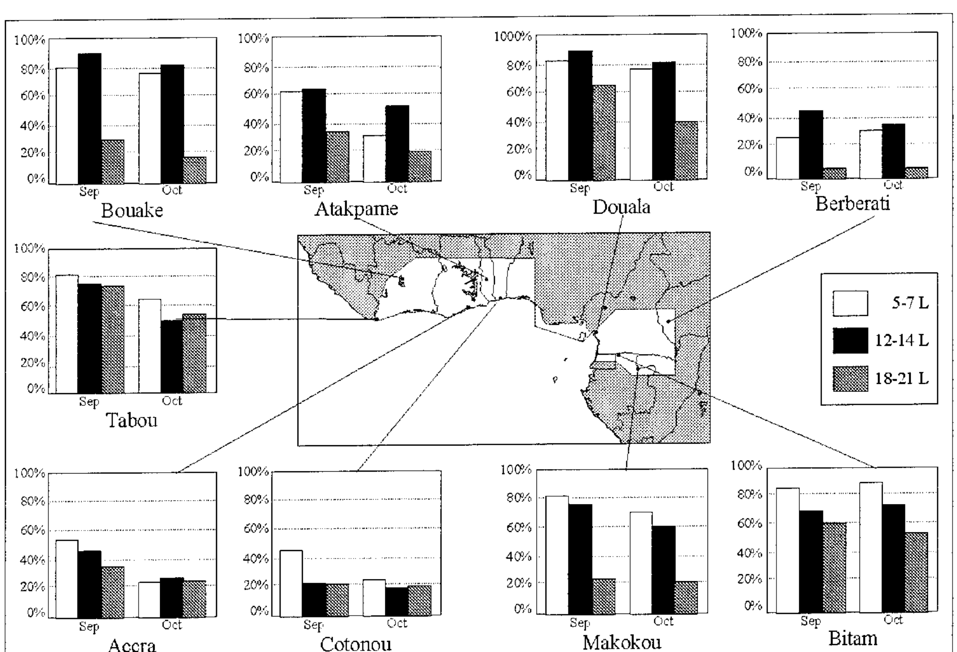


Figure 5-30. Mini Wet Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Visibilities are very good, except in morning fog. Those areas where fog is most common are evident in Figure 5-31. At Bouake, Atakpame, Berberati, Bitam, and Makokou (inland from the immediate coast), fog frequently restricts visibility to less than 800 meters during early morning hours, but it lifts rapidly and dissipates by 1200L.

Showers and thunderstorms occasionally restrict visibilities during the afternoon. Some stations, like Tabou and Douala, also have morning showers and thunderstorms that restrict visibility. Squall lines can reduce visibilities to zero, but they are fast-moving; visibility improves rapidly after passage.

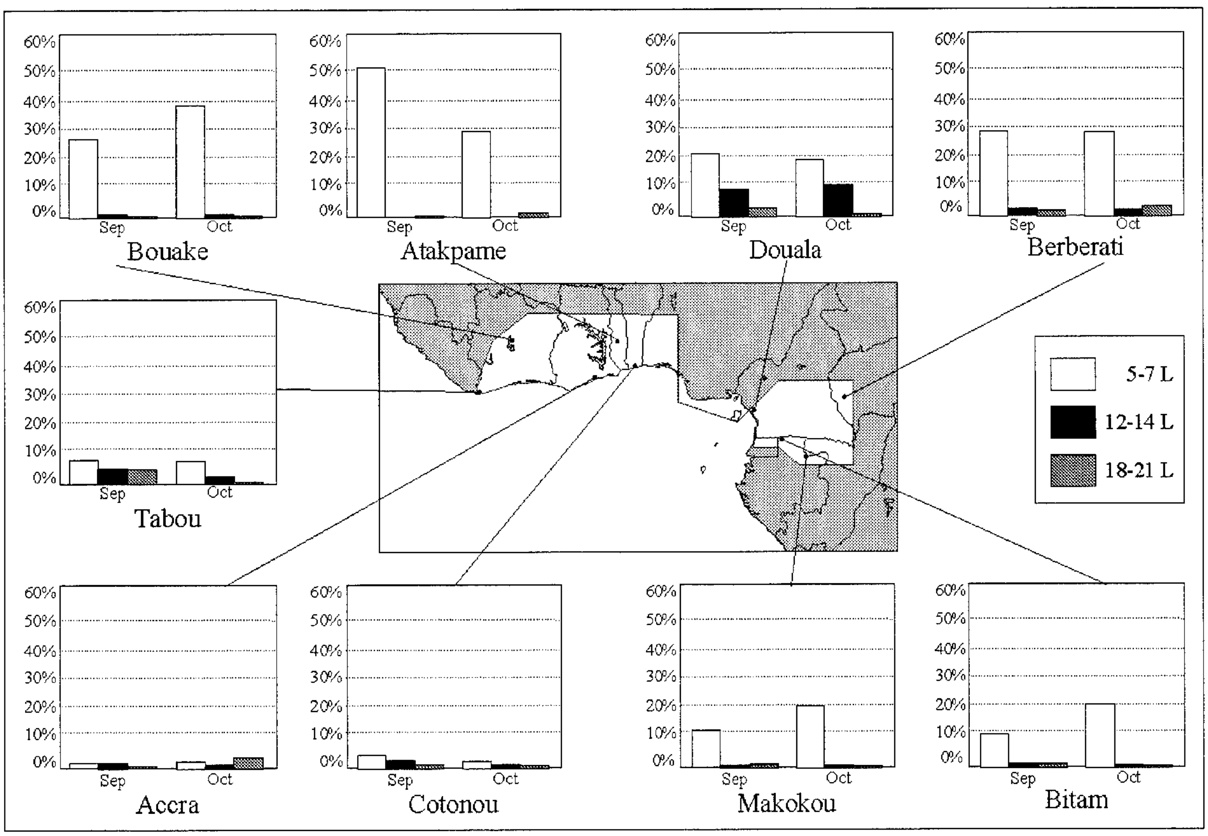


Figure 5-31. Mini Wet Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. The monsoon winds are more pronounced in the western part of the zone, causing stronger surface winds there than in the east (see Figure 5-32). Winds are strongest during the afternoon (see Figure 5-33), but there is no appreciable land/sea breeze circulation. Winds are strongest with squall lines, when gusts of over 30 knots are possible. Upper-air winds are governed by the position of the NET aloft (see Chapter 2).

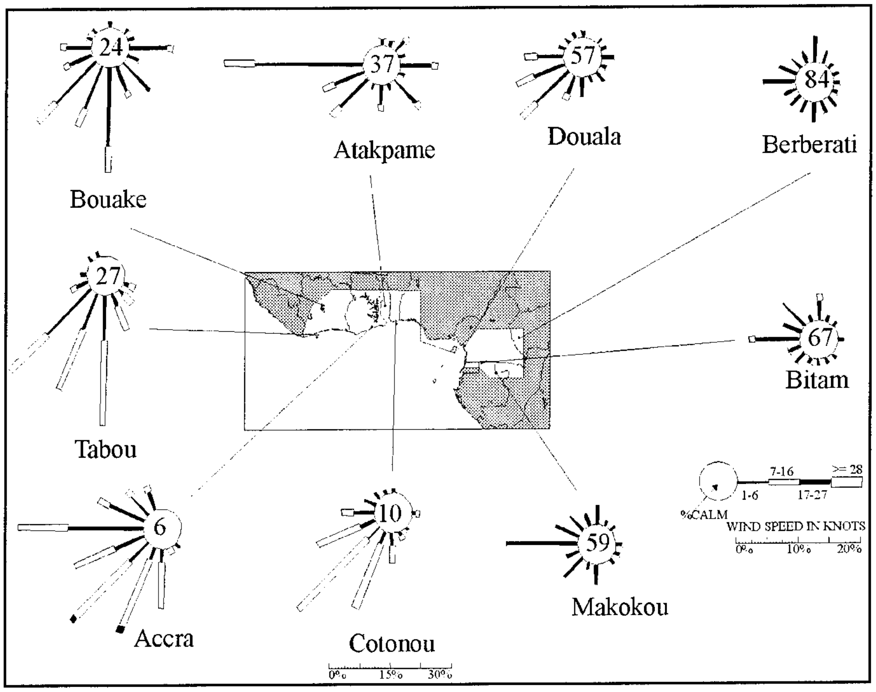


Figure 5-32. October Surface Wind Roses.

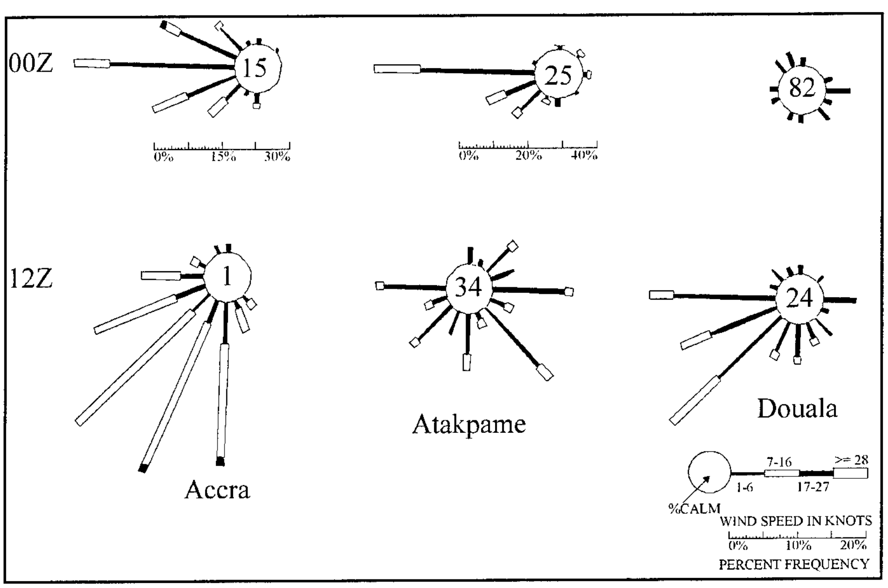


Figure 5-33. 00Z and 12Z Surface Wind Roses for October.

Precipitation. This "mini" wet season is much less pronounced than the main one; the October rainfall maximum is less than the one in June. As mentioned earlier, when the NET moves south rapidly in some years, this season almost goes unnoticed.

As the NET moves south in September, monsoon-type rains begin. Later, air-mass thunderstorms and squall lines become more common. The eastern area receives more rainfall than the west (Figure 5-34), due to the moist onshore flow coupled with the topography of the coastline.

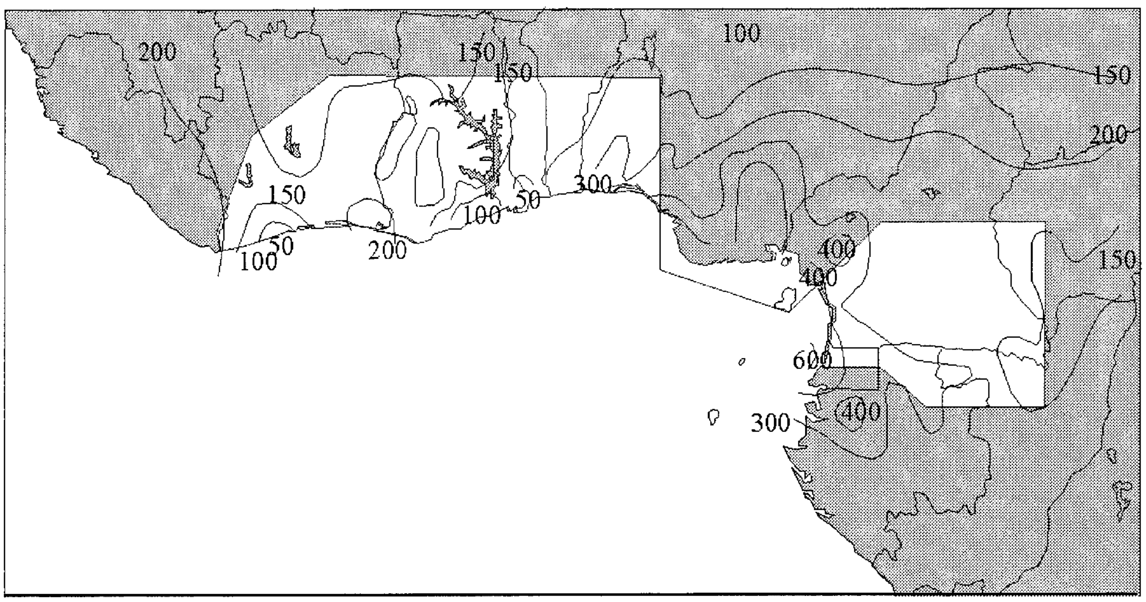


Figure 5-34. October Mean Precipitation (mm).

Thunderstorms can occur at any time of day, but they are most common in the afternoon. Squall lines become more common as the season progresses, and are also most likely to occur in the afternoon. Local flash flooding and minor wind damage is possible. Ceilings may drop below 500 feet during showers, while tops can exceed 40,000 feet. Visibilities may drop to zero with squall-line showers, but they are so fast-moving that visibility restrictions are short-lived.

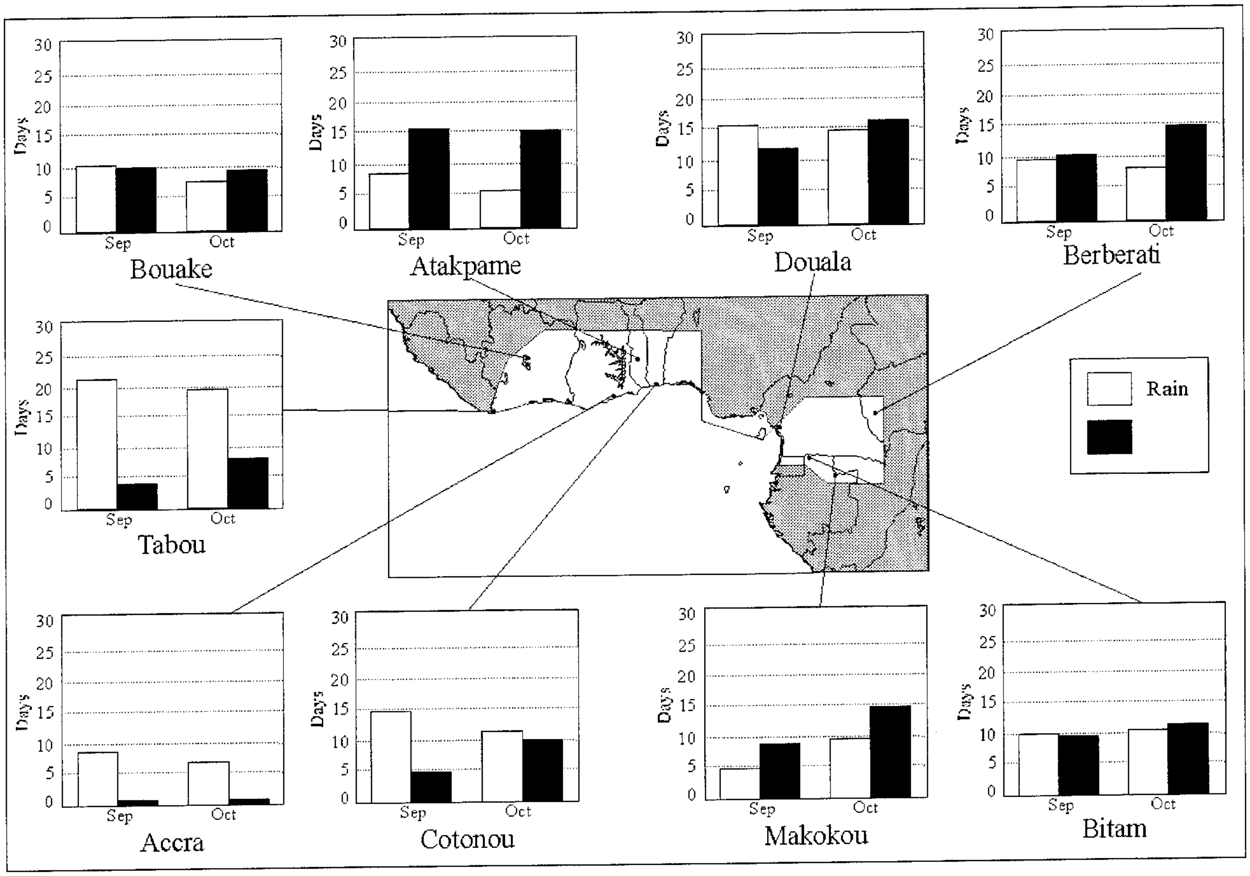


Figure 5-35. Mini Wet Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Mean temperatures show little diurnal change (see Figures 5-36 and 5-37). Extreme highs are in the mid to upper 30s° C. Extreme lows are in the upper teens. The average WBGT is around 30° C.

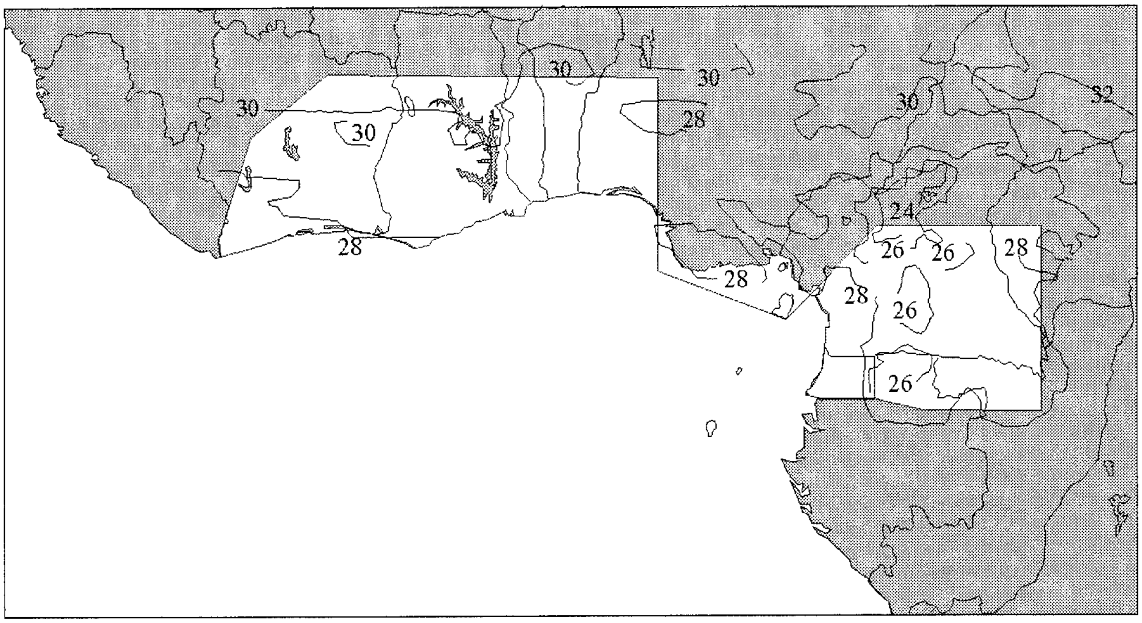


Figure 5-36. October Mean Maximum Temperatures (° C).

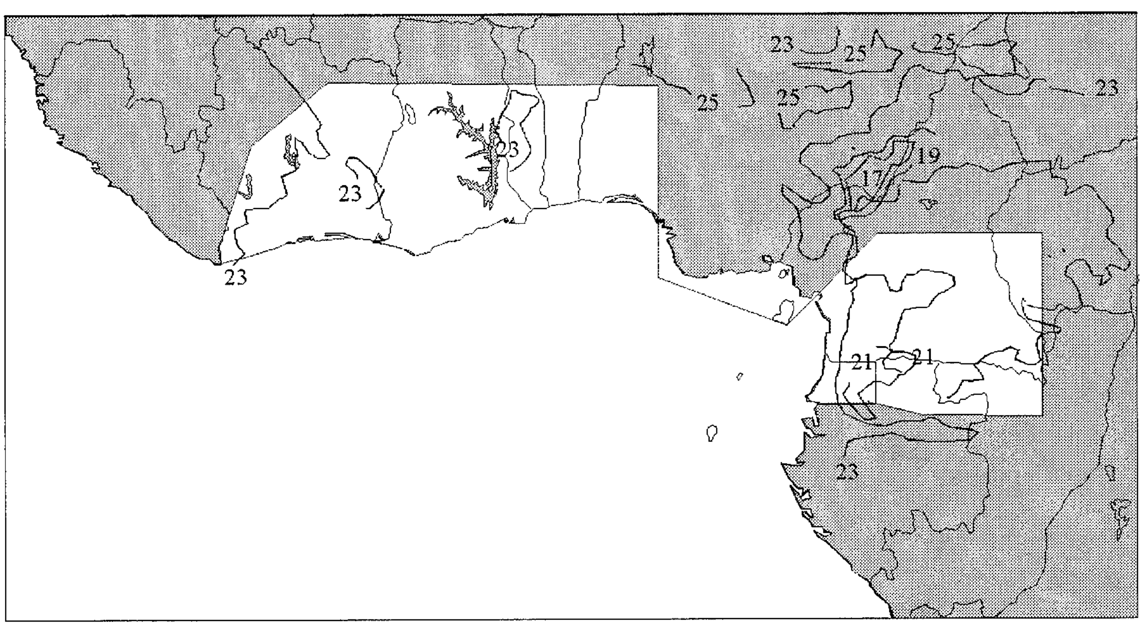
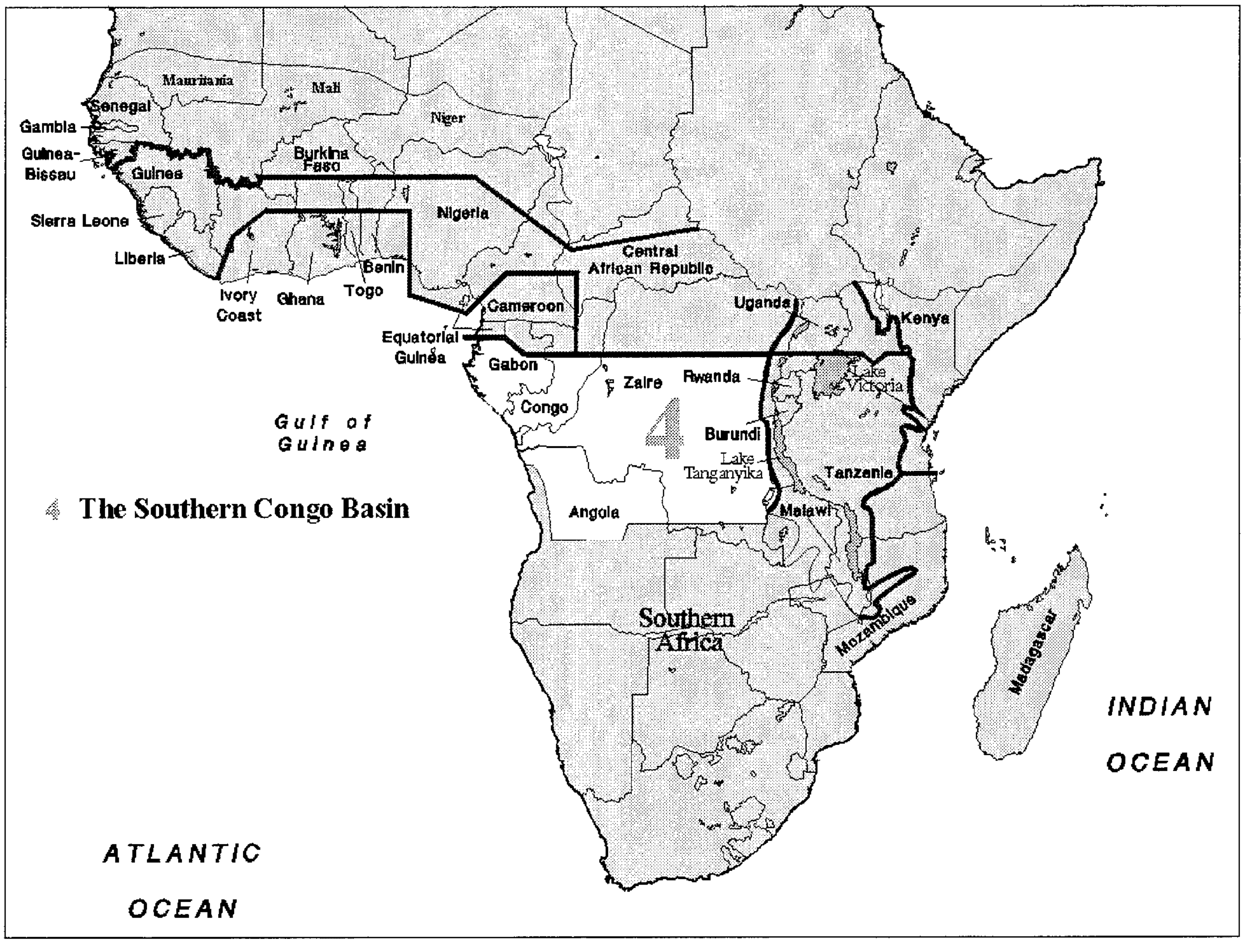


Figure 5-37. October Mean Minimum Temperatures (° C).

Chapter 6

THE SOUTHERN CONGO BASIN

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) for that portion of Equatorial Africa known as the Southern Congo Basin. This "zone of climatic commonality," which covers the southern two-thirds of the Congo Basin proper, comprises the southern parts of Gabon and Congo, the northern part of Angola, and southeastern Zaire.



SOUTHERN CONGO BASIN GEOGRAPHY

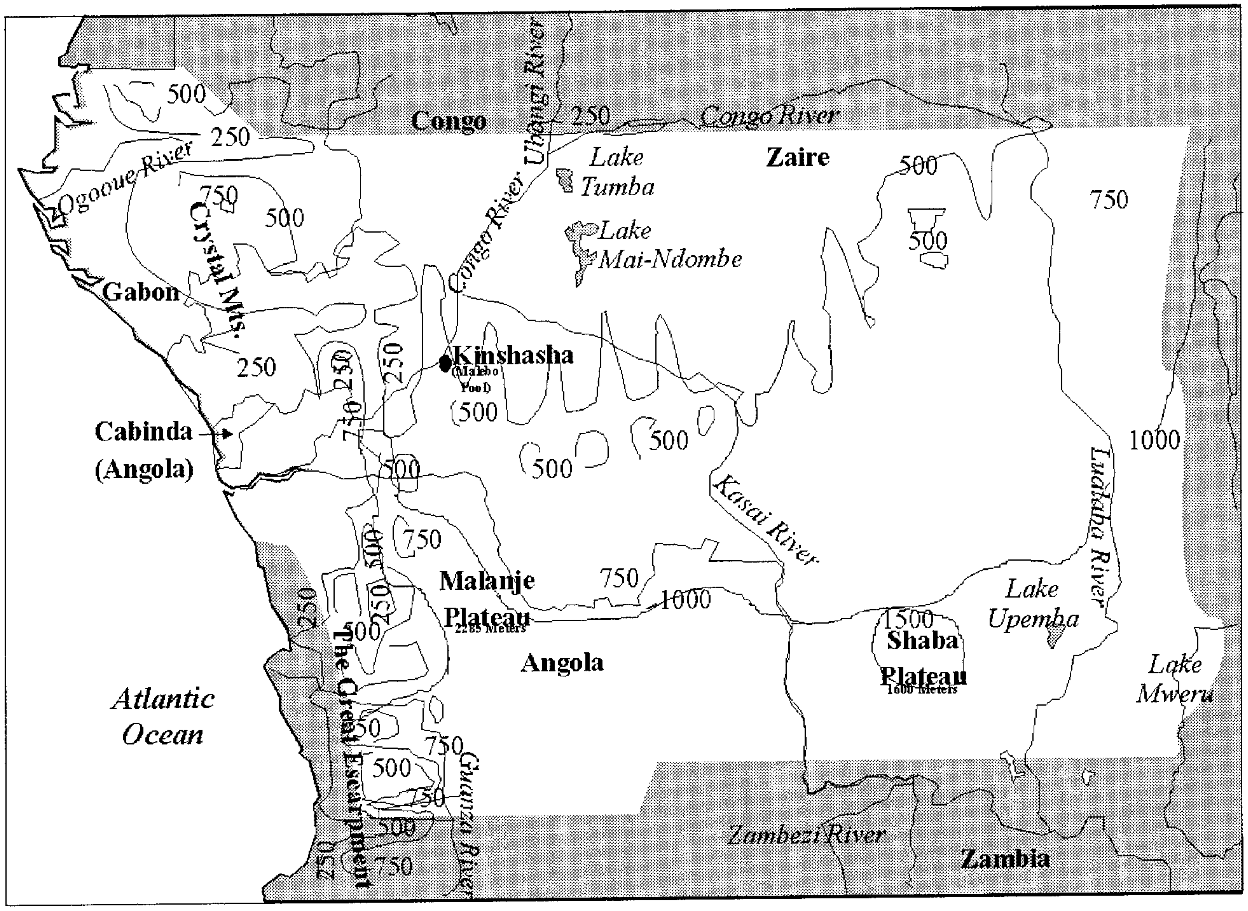


Figure 6-1. Topography of The Southern Congo Basin.

Seasons. The entire zone is very wet; the wet season lasts from October through April, with a short June-August dry season. May and September are periods of transition from wet to dry and from dry to wet, respectively. Seasonal differences between wet and dry seasons become more pronounced as one moves farther away from the equator.

Boundaries. The climatic boundaries of the Southern Congo Basin are based on rainfall seasons. Geographically, the zone runs from the equator south to 12° S; west to east, it extends from 10° E to 28° E. The southern boundary is a line that marks the limit of the rivers that feed into the Congo Basin. The northern boundary begins on the western coast of Gabon, parallels the 1° N longitude line, then follows the equator across Gabon, southern Congo, and Zaire to higher terrain at 28.5° E. It then turns south, parallelling the higher terrain of eastern Zaire. The southern boundary follows the 11° and 12° S latitude lines to the Great Escarpment in western Angola, where it turns north to lower elevations at 13.5° E and 7.5° S and finally turns west to the coast of Angola.

Major Terrain Features. The Atlantic (western) coast consists of a narrow coastal plain backed by mountain ranges. Most beaches on the western border are sandy or rocky, but there are several swamps and lagoons near the mouth of the Congo River.

SOUTHERN CONGO BASIN GEOGRAPHY

In the north, coastal terrain rises rapidly inland to form the Crystal Mountains, which parallel the coast from northern Gabon to northern Angola and reach elevations of 1,000 meters in southern Gabon. Average width is 540 km. Farther south, the Great Escarpment runs along the coast, rising to over 750 meters. Once across the coastal mountains inland, terrain slopes gently upward.

The Congo River Basin dominates the region; average elevation is 520 meters. The lowest point is 338 meters at Lake Mai-Ndombe. The highest point is 700 meters along the Ubangi River.

Farther south, the Southern Congo Basin slopes upward to become a series of plateaus. On the Malanje Plateau in the southwest, peaks reach 2,285 meters. In the southeast, the large Shaba Plateau rises to 1,600 meters.

Rivers and Drainage. The Congo River (also called the "Zaire," an African word for "big river") dominates the region. The river's 4,700-km length drains a basin of over 2.6 million square km from 12° S to 8° N. Because the Congo drains both the Southern Congo Basin and the Northern Equatorial Belt, its depth is more stable than most of the rivers in Africa even though it rises significantly during the wet season.

The Congo originates in the southeast as the Lualaba River and runs northward, becoming the Congo as it crosses the equator. After describing a sweeping arc just north of the equator, it flows southwestward toward its mouth south of Cabinda. Because of the steep descent and resulting rapids, the Congo is not navigable downriver from Kinshasha (Malebo Pool) to the ocean. Just downriver from the pool is Bolo Falls. Short railroads, however, provide portages around the falls and rapids. Malebo Pool is navigable to ships up to 1,200 tons. Since most of the Congo is navigable (the current is, in fact, sluggish from Kinshasha to the equator), it is the main transportation artery into central Africa.

The Congo Delta is about 180 km long and 10-15 km wide. Although it contains violent whirlpools, the main channel is navigable by ocean-going vessels. Tides are noticeable about 100 km upriver.

The Congo has many tributaries; two of the most important are the Ubangi and Kasai Rivers. The confluence of the southward-flowing Ubangi and the Congo forms a great swamp that stretches through most of the zone's north-central area. The Kasai River has its source on the Shaba Plateau; it runs along Angola's border with Zaire before turning northwestward. The Kasai is about 1,900 km long, most of which is navigable. Gabon's chief river, the Ogooue, is one of the major watersheds in Africa. The Cuanza (about 1,000 km), is the principal river in northern Angola.

Lakes and Reservoirs. Lake Mweru, which lies in the southeastern part of the zone with an area of about 7,000 sq km, is the largest lake in the Southern Congo Basin. It forms the eastern headwaters of the Congo River. Large swamps line its eastern shores, while hills rise along the western side. Lake Upemba is the largest of the many small lakes that line the banks of the Lualaba River.

Lake Mai-Ndombe is a shallow, irregularly shaped lake in the north-central part of the zone. Its size changes dramatically from season to season. Its name ("black waters") refers to the high concentration of tannic acid. Its banks are heavily forested. Lake Tumba, which drains into the Zaire (Congo) river, is shallow with low shores.

Vegetation. Most of the region is covered with dense tropical rain forest and savanna grasses. In the center of the basin is an equatorial rain forest where trees grow to massive heights. Trees include the hardwood okoume tree, African teak, red cedar, and walnut. The plateaus and large valleys contain mostly savanna type vegetation, coconut palms, and banana trees. Coffee plantations flourish on plateaus. Less than 5% of the region is suitable for cultivation because of poor soils.

MAJOR CLIMATIC CONTROLS OF THE SOUTHERN CONGO BASIN

Near EquatorialTrough (NET). The NET is one of the main features affecting the Southern Congo Basin. Convergence along the NET causes most of the zone's convection. The NET is at its southernmost position in January (the middle of the wet season), and at its northernmost position in July (the middle of the dry season). See Chapter 2, Figures 2-6a through l for mean positions of the NET.

Congo (Zaire) Air Boundary (CAB). The CAB is a convergence zone between the outflow of Indian and Atlantic Highs. The CAB's effects are most pronounced during the wet season, due to the increased moisture and instability of the air mass that influences the area. Although convection along the boundary is usually capped by subsidence during the dry season, it still accounts for much of the convection during the dry season and the two 1-month transition periods.

The "Zaire Thermal Low." Also called the "Continental Low " or "Zambia Low," this thermal low-pressure area persists over Equatorial Africa during most of the year. It develops as land areas heat up while the oceans remain relatively cool. This system contributes to surface convergence, especially during the wet season when it is at its greatest strength. During the dry season, it moves to the north, but there is still substantial troughing over the area.

General Weather. From December through March, the NET is oriented roughly northwest through southeast, stretching from the northern Congo border along the eastern portion of the region. As the Zaire thermal low develops, there is an increase in surface convergence. This pattern results in abundant convective rains; the greatest amounts fall closer to the equator and at higher elevations.

Temperatures in the region are generally in the high 20s ° C. Relative humidities are very high; 95% is common in the morning. High temperatures and high humidities combine to result in oppressive conditions.

Flow from the Sahara may occasionally invade the area, producing clear and dry conditions, with brief episodes of Harmattan haze.

Sky Cover. Wet-season cloudiness resembles that associated with a tropical maritime air mass. As shown in Figure 6-3, ceiling frequency increases from north to south. Stratocumulus (with pockets of status) is common in the morning, especially along the coast. Stratus dissipates by late morning. Convective clouds develop later in the day, especially over the warmer inland regions. By late afternoon, clouds cover most of the area, with frequent rainshowers and thunderstorms. Convection is enhanced at higher elevations. Clouds decrease in the early evening, with stratus re-forming during the night. In the morning, broken to overcast stratus ceilings range from 300 to 900 feet; they are generally less than 900 feet thick over land, but slightly thicker in valleys. Cumulus bases are from 2,000 to 3,000 feet. Thunderstorm tops can reach 50,000 feet. Nimbostratus can lower overcast bases to less than 300 feet.

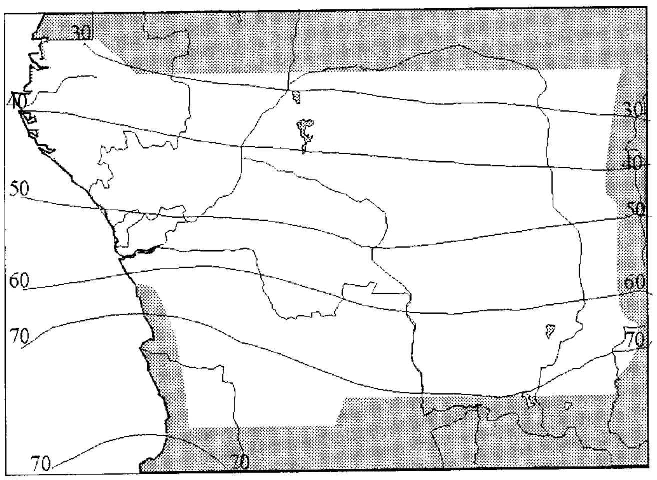


Figure 6-2. Wet-Season Percent Frequencies of Ceilings.

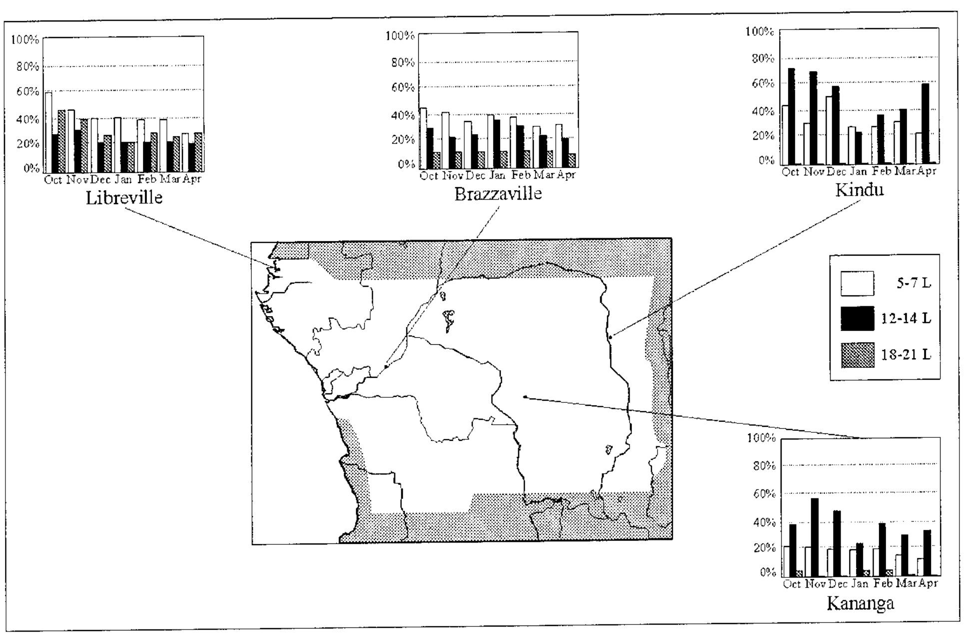


Figure 6-3. Wet-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Although wet-season visibility is generally good, coastal regions can have visibilities near 800 meters during late night and early morning hours. In other parts of the zone, early morning visibilities of 3,200 to 8,000 meters in fog are common, but the fog dissipates by mid- to late morning.

The north-central portion of the area is especially vulnerable to fog and haze. Fog forms in this low-lying, swampy area when the moist, stagnant air mass, surrounded on all sides by higher elevation, cools overnight. Visibilities here are 1,600 to 6,000 meters in early morning, increasing to 16 km by late morning or early afternoon. Local effects may produce slightly worse conditions, and sheltered areas may not break out of the fog and haze until mid-afternoon. A previous night's rain can also result in lower visibilities.

Rainshowers generally reduce visibility to between 6,000 and 9,000 meters. In heavier thunderstorms, visibility can be 800 meters or less. Harmattan haze (dust from the Sahara) is rare, but it can occur in the northern portion of the area in the dry season; since it is usually confined to above the lower moist layer, visibilities get worse at about 900 meters and above. Once afternoon heating stabilizes the atmosphere, some mixing of the haze can occur down to the lower moist layer. Visibilities seldom fall below 4,800 meters in Harmattan haze.

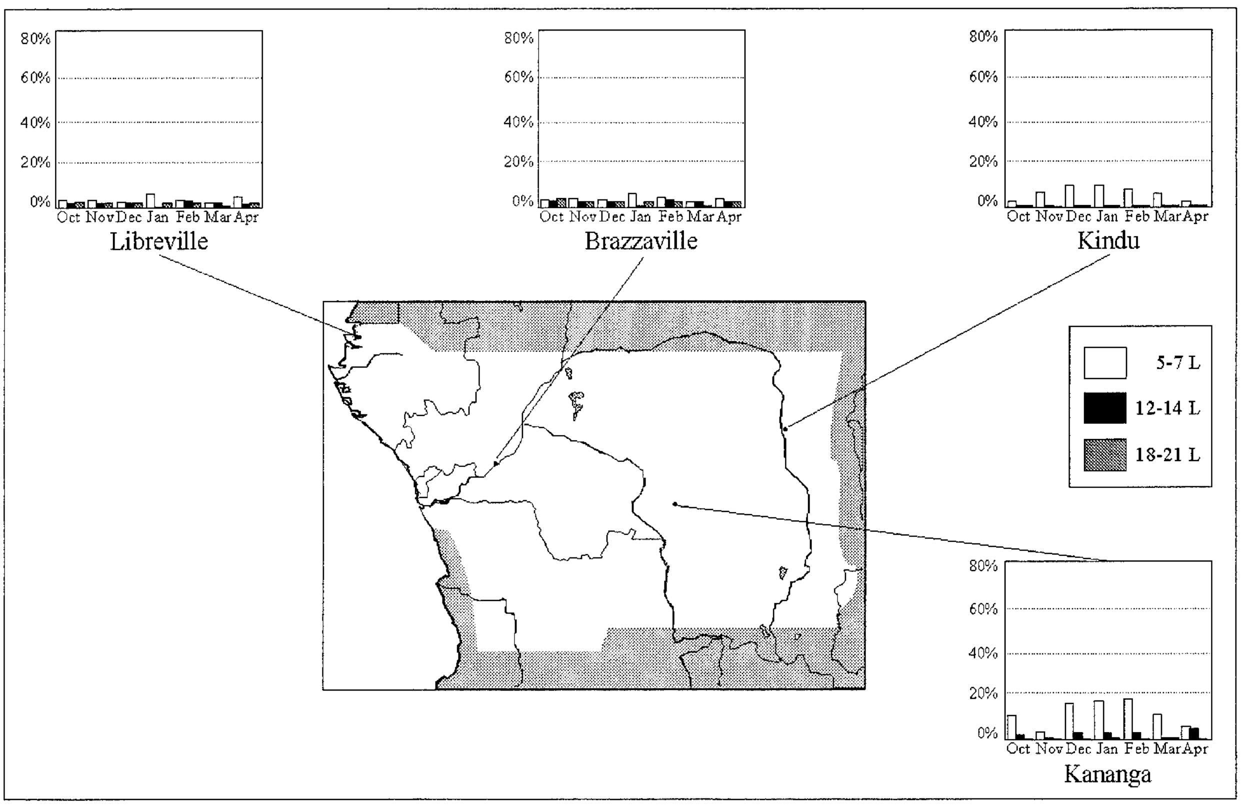


Figure 6-4. Wet-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. The position of the NET determines the prevailing wind, which is generally southerly to westerly and light when the region is under the influence of the South Atlantic High. In the interior (except for convective activity), only 4 days a year see speeds greater than 27 knots. Convective wind gusts of up to 75 knots have been recorded, usually associated with squall lines. Winds aloft generally have an easterly component.

Diurnal wind patterns are strong in the mountains and along the coast, where there is a complete diurnal reversal in wind direction. Winds are strongest on the coast because of the cool Benguela current and upwelling of colder subsurface water. A strong sea breeze that sets up in the afternoon is the strongest gradient wind in the area; it can reach 20 knots when channeled through terrain.

Hot and dry winds from the Sahara are occasionally reported throughout the zone. They last for 3 or 4 days, wilting crops and decreasing the humidity. Sometimes these winds can be produced locally from terrain effects and drier flow.

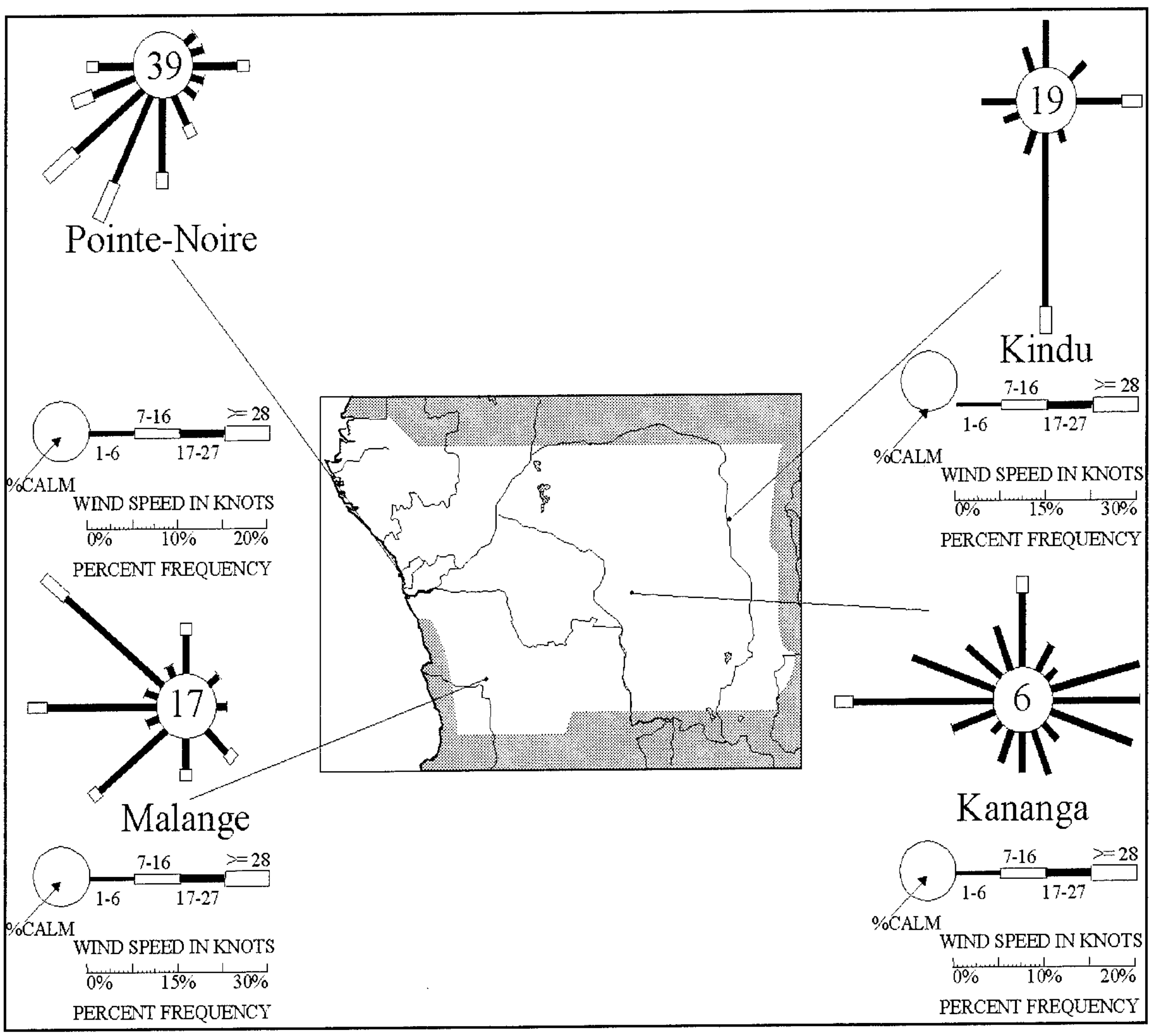


Figure 6-5. January Surface Wind Roses.

Precipitation. Convective precipitation accounts for most rainfall over the area. The highest amounts are found in the northern regions near the equator (see Figure 6-6), where about 1,700 mm falls annually. Although most rain falls in the wet season, it can rain here the year-round. Stations on the equator have reported maximum monthly values up to 355 mm a month during the wet season. Farther south, the distinction between the wet and dry seasons is better defined. The southern part of the zone gets 95% of its annual rainfall from October through April. This area's annual rainfall average is 1,066 mm, with a monthly wet-season average of 152 mm. Monthly precipitation amounts vary from year to year over the entire area, and convective precipitation can be extremely localized; recorded amounts have exceeded 75 mm in 30 minutes.

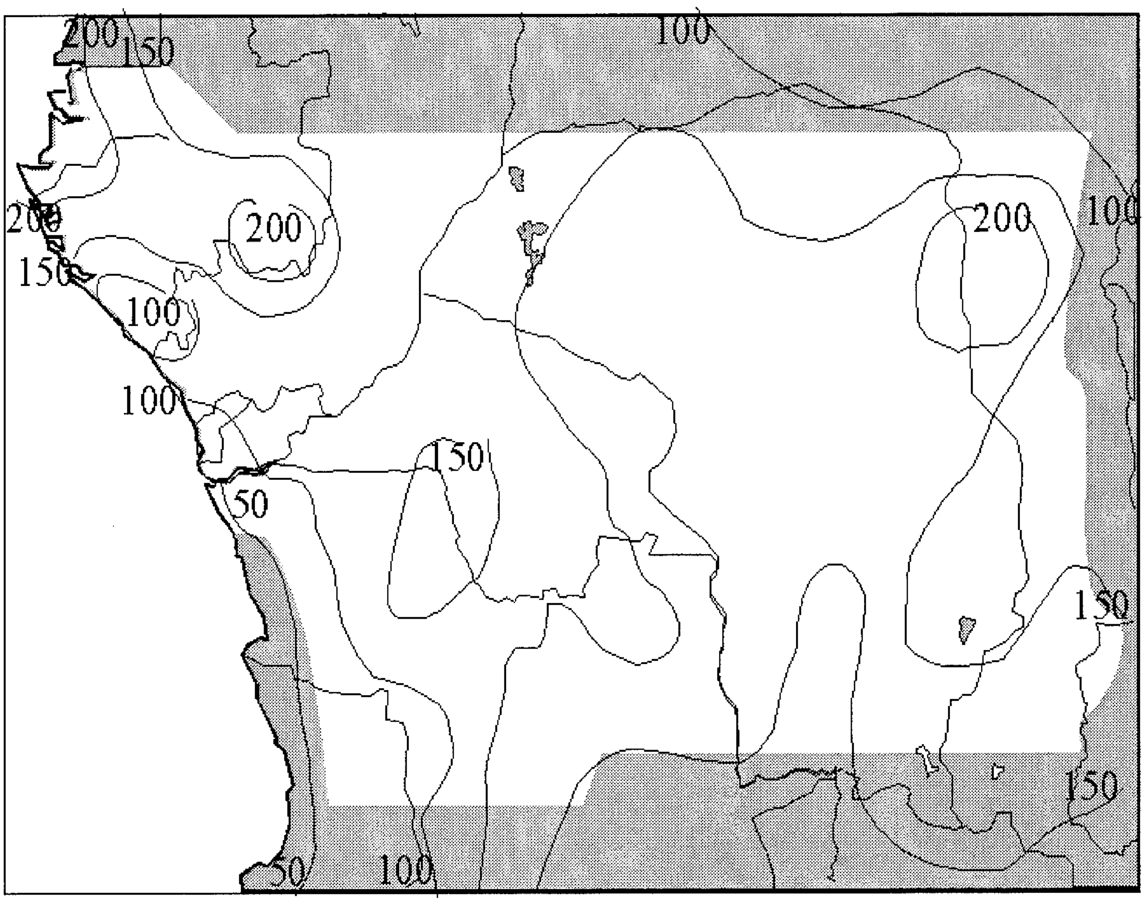


Figure 6-6. January Mean Precipitation (mm).

Thunderstorms. Isolated thunderstorms occur frequently from afternoon through early evening, normally dissipating after sunset. Evening and early morning thunderstorms are usually associated with either squall lines or mesoscale convective systems that form along the Atlantic coast and move slowly inland. Isolated thunderstorm bases are normally between 2,000 and 4,000 feet, with tops between 35,000 and 45,000 feet. Wind gusts are generally less than 25 knots. Thunderstorms associated with squall lines and mesoscale convective systems can have tops above 50,000 feet. Average gusts for this type of thunderstorm are still normally less than 25 knots. Squall lines (called "African tornadoes" because of their heavy precipitation, strong winds, and frequent lightning) originate near the Congo Air Boundary. These violent systems move from east to west across the Southern Congo Basin. Ceilings and visibilities decrease to near zero at times; winds can exceed 50 knots, and downbursts are common. Precipitation can exceed 75 mm in 30 minutes with the passage of a squall line. Blowing dust associated with squall lines is more prevalent during the dry season, but it can also occur in the wet season.

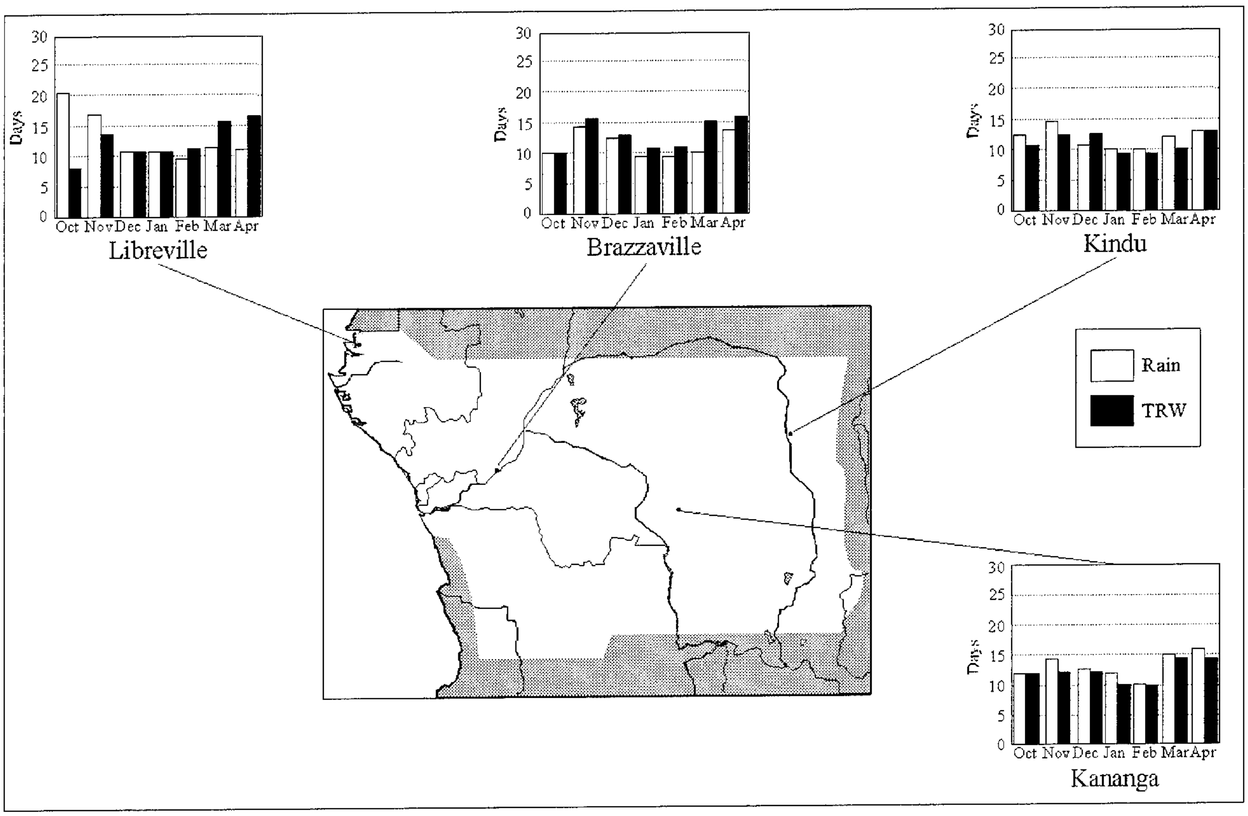


Figure 6-7. Wet-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Although there isn't much annual variation in temperature this close to the equator, wet-season temperatures are slightly warmer than during the dry season. Extreme maximum temperatures in February are 41° C in equatorial Gabon and 40° C along northern Angola's plateau. Extreme minimum temperatures can dip to 0° C in the high Angola plateau area near the end of the wet season. Because of the high humidity, diurnal temperature variations average less than 11° C, except at higher elevations. Average wet-bulb globe temperatures in the southeast are 24° C in October and April; in the northeast, they average 30° C all season long.

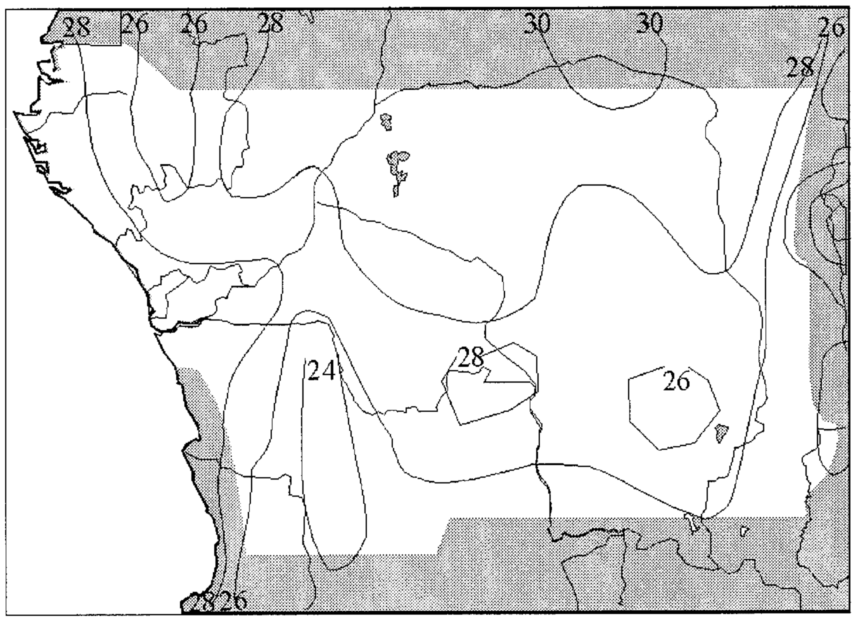


Figure 6-8. January Mean Maximum Temperatures (° C).

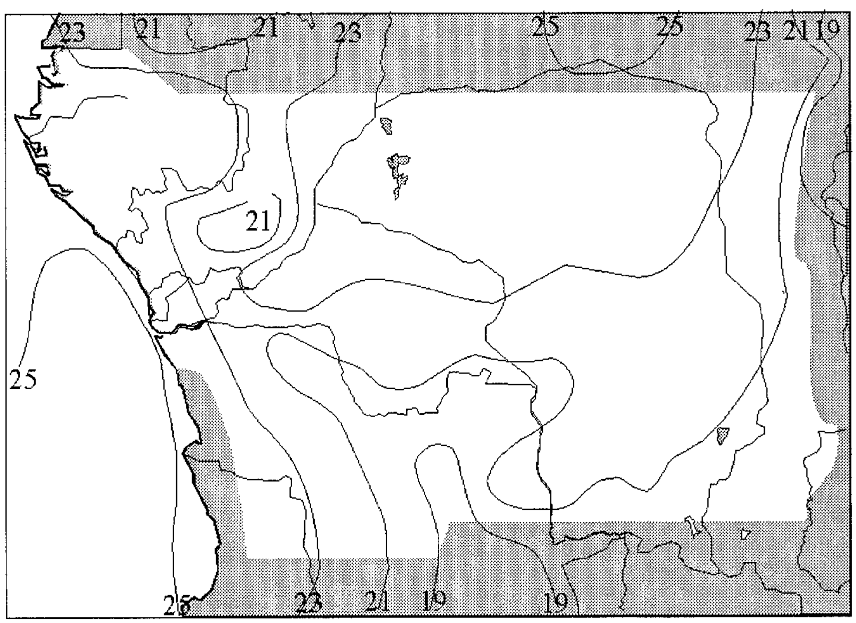


Figure 6-9. January Mean Minimum Temperatures (° C).

General Weather. Although the dry season is hardly noticeable near the equator, it becomes more pronounced farther south. June is slightly drier near the equator, while May through September are decidedly drier in the southernmost portion of the zone. During the dry season, a stable and stagnant air mass resides over the region, with a very slight decrease in temperatures. Relative humidities remain constant in the north and central low-lying areas, but decrease slightly in the south. Smoke from burning savanna grasses is common during the dry season. Polar maritime air that originates in the mid-latitudes may reach the area occasionally, producing cooler temperatures and reduced humidities.

The NET, oriented east-west, moves north of the equator during the dry season. The Zaire low becomes less well-defined as a weak, broad low-pressure trough that extends southward from the equator. High-pressure ridging from the South Atlantic and Indian Ocean highs become the dominant upper-air features. Subsidence of the highs dampens convective activity over the southern portion of the zone. The convective activity that still occurs is usually restricted to the northern portion of the area.

Sky Cover. Since the northern portion of the region continues to be influenced by the NET, skies are still cloudy there (Figure 6-10). Subsidence caps most convection in the south, but morning stratus is still common. The coastal regions of the Southern Congo Basin see their maximum cloudiness during the dry season. The stability and abundant moisture along the coast combine with the cold Benguela Current to produce widespread stratus decks with bases from 200 to 1,000 feet.

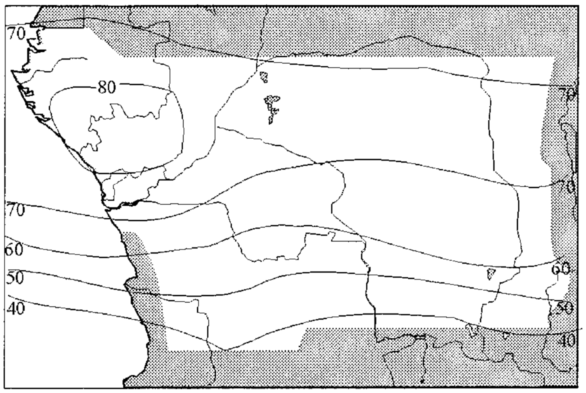


Figure 6-10. July Percent Frequencies of Ceilings.

The general characteristics of the moist Southern Congo Basin air mass don't differ much from the wet season; stratus and stratocumulus are still common in the morning hours. Bases range from 300 to 1000 feet. The stratus is generally less than 1,000 feet thick over land, but slightly thicker in river valleys. The eastern and southern portion of the Southern Congo Basin are generally influenced by the Indian Ocean air mass. The flow, which crosses higher terrain before it gets to the area, is slightly drier than the flow from the Atlantic and stratus forms less frequently. The southern plateau area reports many cloudless days after solar heating dissipates morning stratus. Thunderstorm tops can still reach 50,000 feet.

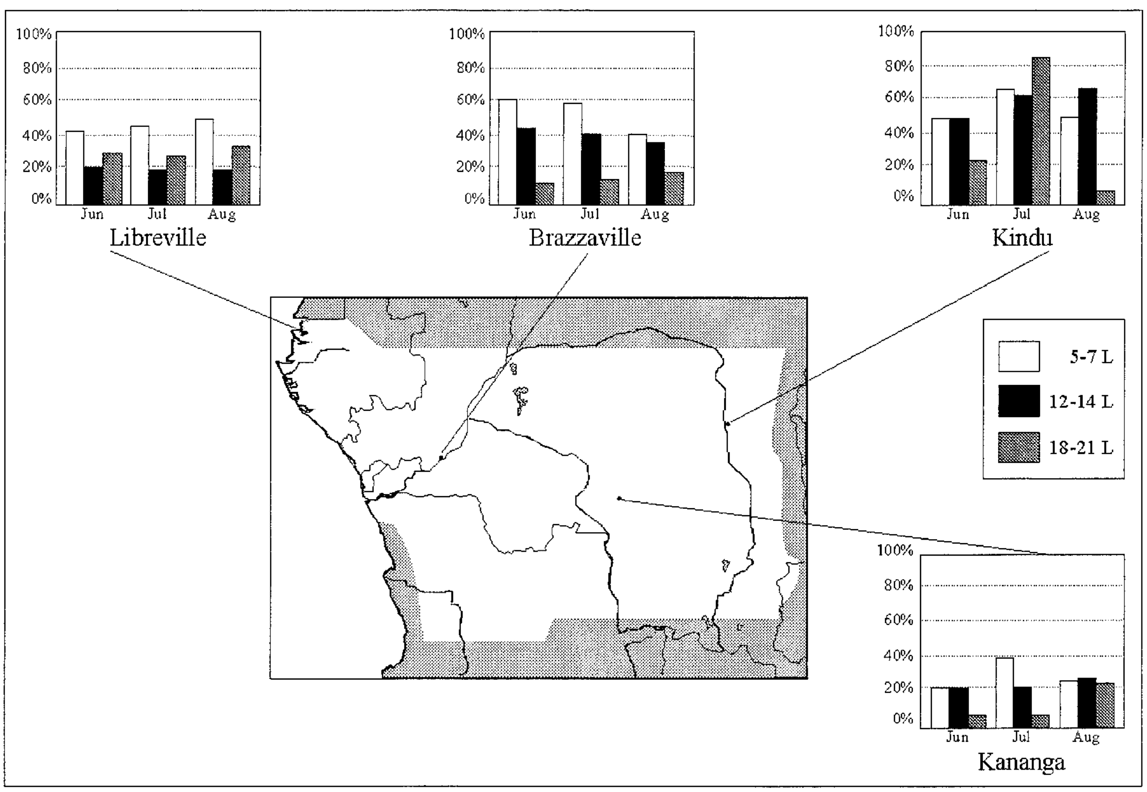


Figure 6-11. Dry-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Because subsidence traps moisture, dust, and smoke in the lowest layers of the atmosphere, visibilities are generally poorer during the dry season. Morning visibilities are often 3,200 meters. Note the high frequency of poor visibility at Kananga and Kindu in Figure 6-12. The burning of savanna grasses and farm fields contributes to the build-up of pollutants during the dry season. Dust raised by occasional strong winds or thunderstorms can reduce visibility to less than 1,600 meters. Although Harmattan haze is rare in the southern part of the zone, it can occur; because the haze is usually confined above the lower moist layer, visibility aloft is often worse than at the surface. Once afternoon heating has destabilized the atmosphere, some mixing of the haze can occur, reducing visibilities at the surface. With increased stability, dense fog forms along the coast during the dry season. Visibilities of less than 1,600 meters have been reported over a 3-4 day period at some coastal stations.

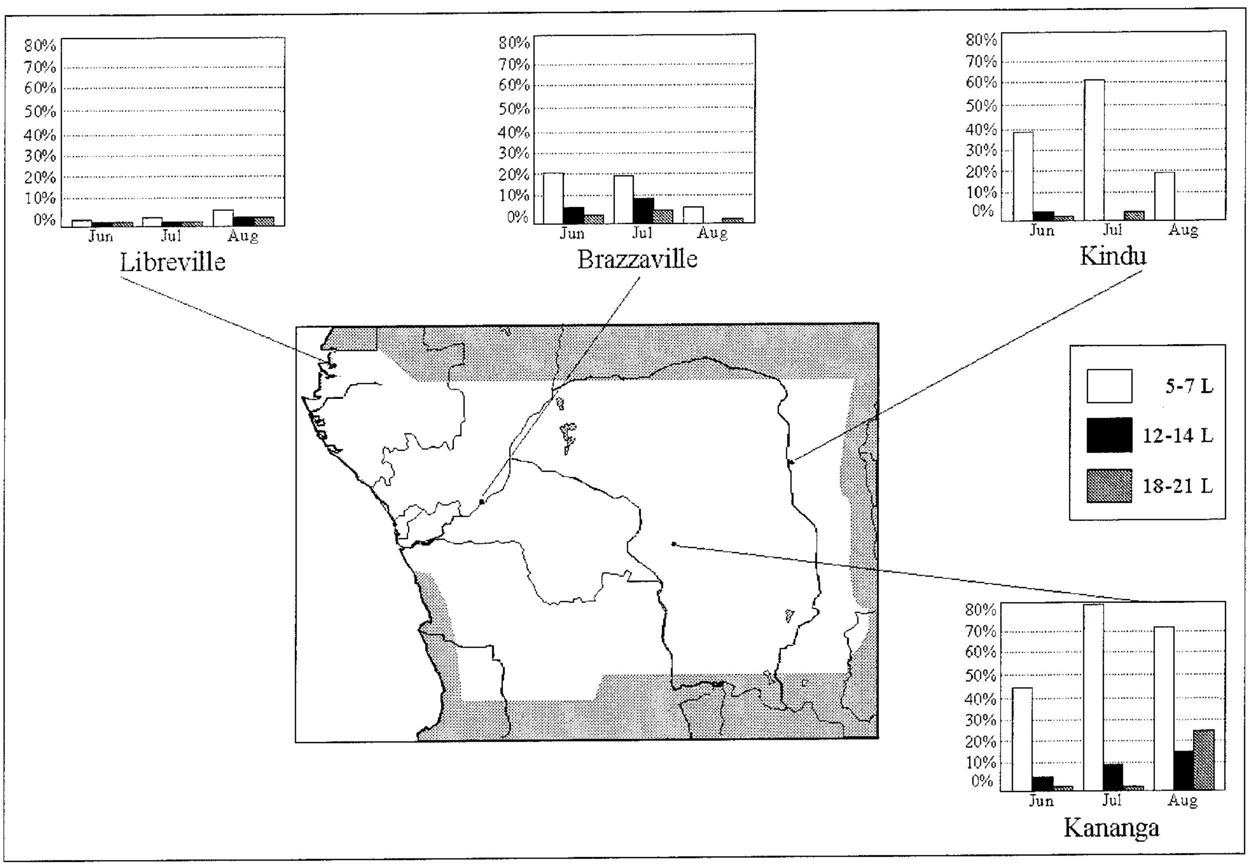


Figure 6-12. Dry-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. In the southern portions of the zone, winds are southeasterly in the interior and southerly along the coast. Near the equator, winds are more variable. Wind flow is driven by the Indian Ocean High in the eastern portion of the zone and by the Atlantic High in the west.

Because the ocean currents are cool and the landmass is relatively warm, a sea-breeze circulation forms in the afternoon along the coast. The sea breeze is the strongest gradient wind in the area; it can reach 20 knots when channeled through mountain valleys.

As Indian Ocean air passes over higher terrain on the eastern and southern portion of the African Continent, it becomes hotter and drier; speeds are generally less than 15 knots. A hot wind can also accompany occurrences of Harmattan haze.

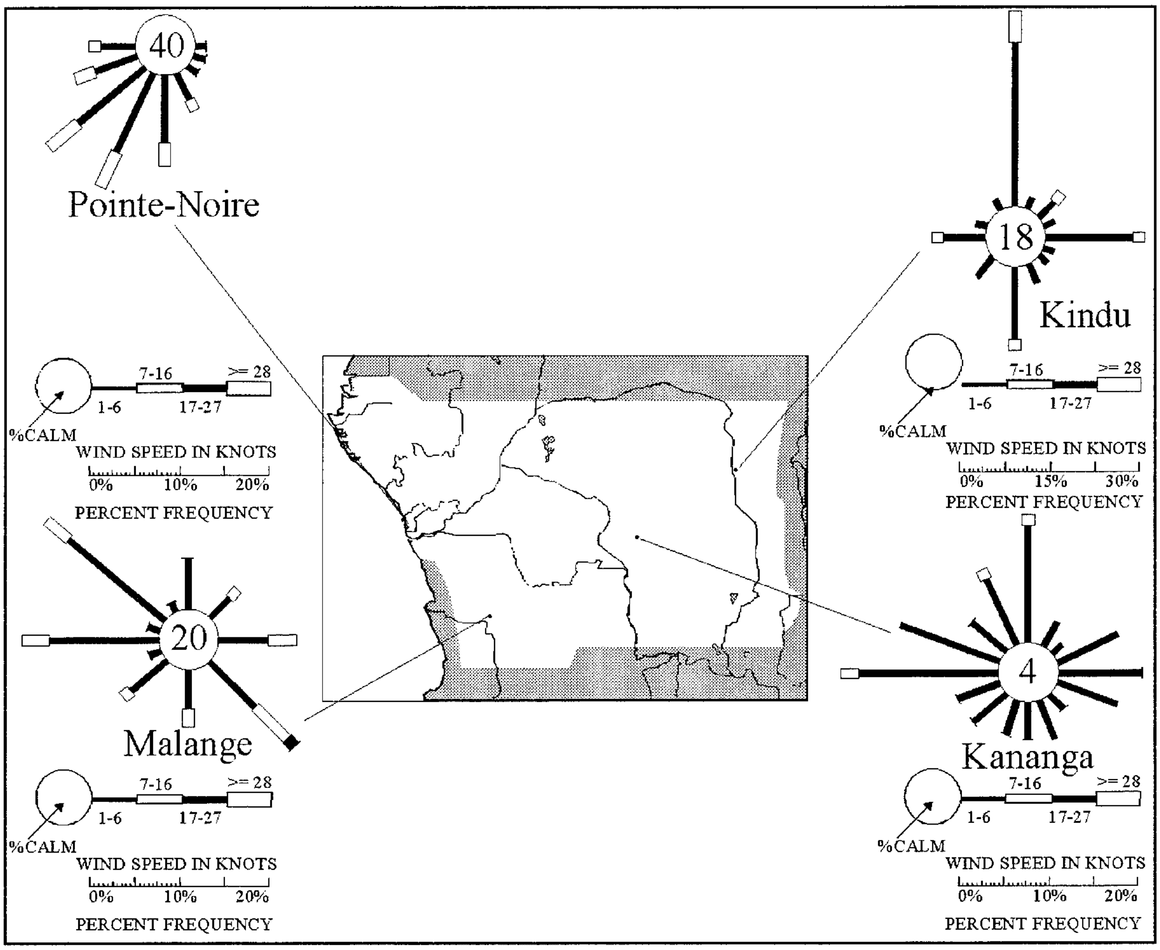


Figure 6-13. July Surface Wind Roses.

Precipitation. Convective precipitation still accounts for most dry-season rainfall. The highest amounts fall close to the equator (see Figure 6-14). Convection becomes less common to the south. Average monthly precipitation amounts range from less than 10 mm in the south to 150 mm in the north. Convective precipitation can be extremely localized. With downbursts, amounts have exceeded 75 mm in 30 minutes. Monthly precipitation amounts can also vary greatly from year to year. Even though there are more days with precipitation in coastal areas than in other parts of the zone (see Figure 6-15), most coastal precipitation falls as drizzle or light rain, with little accumulation. The southern plateau area receives hardly any precipitation during the dry season.

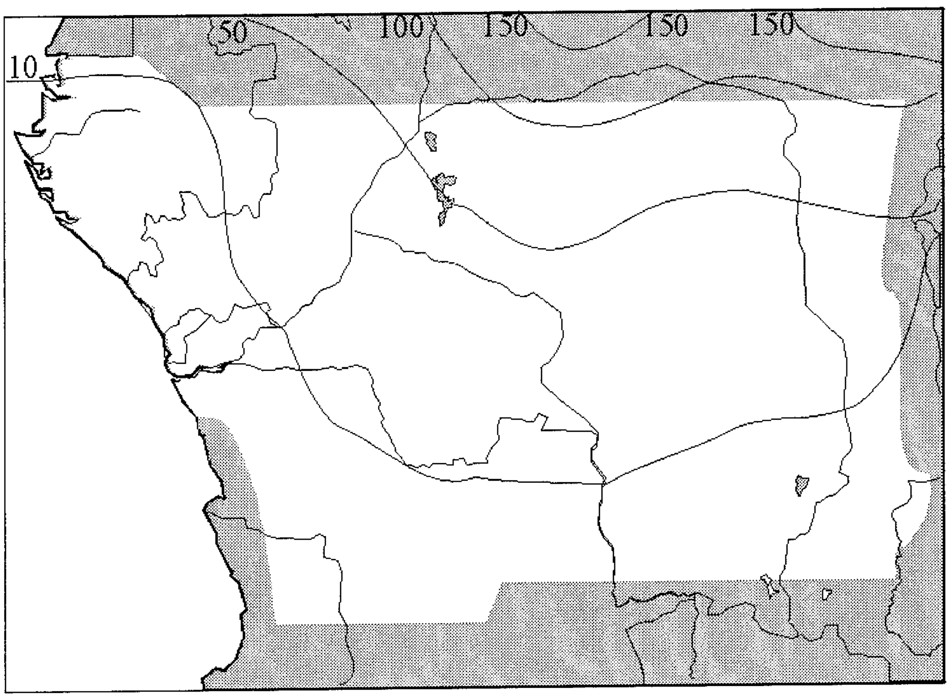


Figure 6-14. July Mean Precipitation (mm).

Thunderstorms. The frequency of dry-season thunderstorms drops dramatically as one moves away from the equator. While Kindu has only 5 thunderstorm days a month (or fewer; see Figure 6-15), areas to the north see thunderstorms on as many as many as 14 days a month. Since dry-season cumulus development in the south is usually capped by an inversion, thunderstorms are much less frequent there; on the central and southern plateau, there are only 3 thunderstorm days a month, or fewer. Isolated thunderstorms occur mainly during late afternoon, with bases between 2,000 and 4,000 feet and tops from 35,000 to 45,000 feet.

Average wind gusts in isolated thunderstorms are generally less than 25 knots. Squall lines, called "African tornadoes" because of their heavy precipitation, strong winds, and frequent lightning, originate near the Congo Air Boundary. These violent squall lines move from west to east across the Southern Congo Basin, lowering ceilings and visibilities to near zero. Winds can exceed 50 knots with downbursts, and 75 mm of rain can fall in 30 minutes. Blowing dust, which often accompanies squall lines during the dry season, can reduce visibility to 800 meters Thunderstorm tops can exceed 50,000 feet.

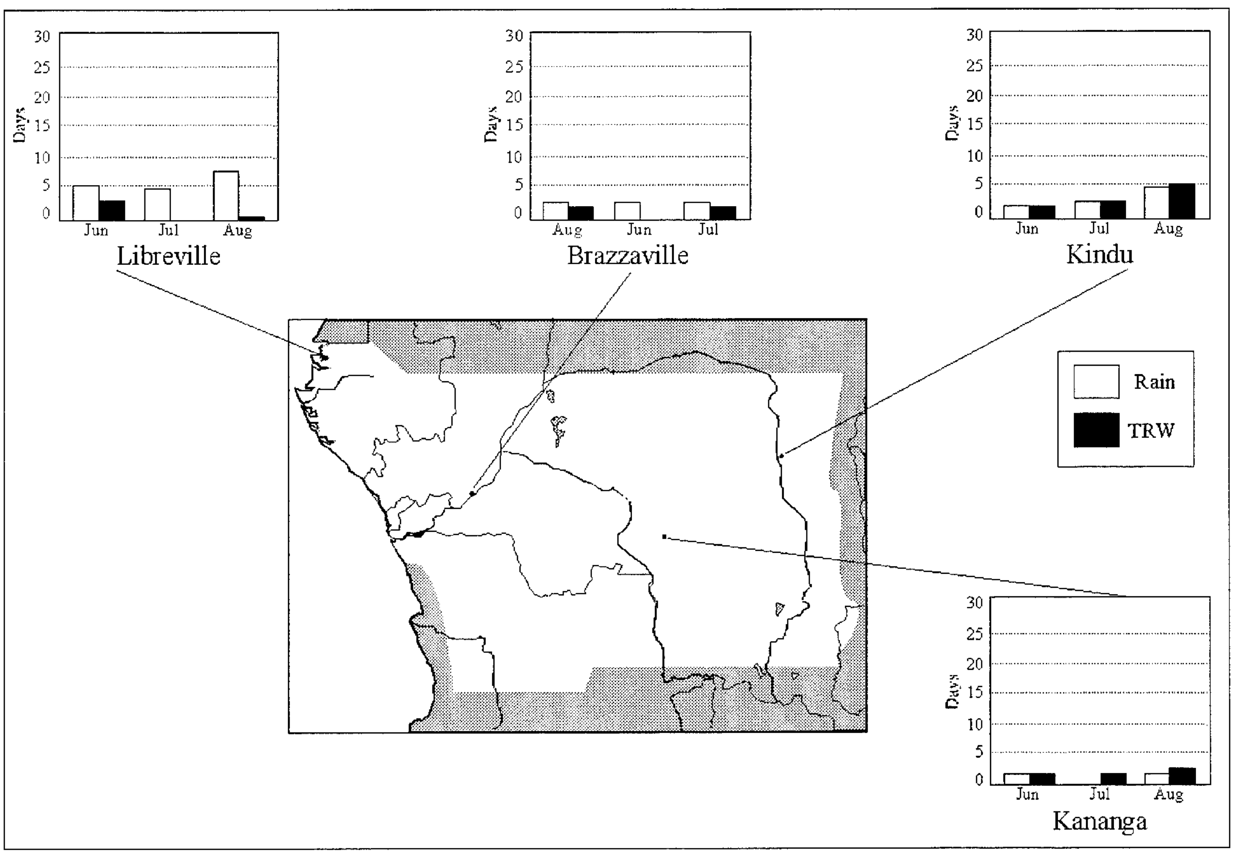


Figure 6-15. Dry-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Minimum dry-season temperatures vary widely across the region, ranging from extremes of 22° C in the central and northern portions to -2° C on the southern plateau, where occasional light frosts have been observed. Extreme lows are usually associated with maritime polar air masses that originate in the mid-latitudes. The highest temperatures during the dry season are recorded in July; they include 38° C in the Central Zaire basin and 37° C along northern Angola's plateau. Mean high and low temperatures are shown in Figures 6-16 and 6-17. Although diurnal temperature variations are more pronounced in the south, variation in the north remains at about 11° C. Average wet-bulb globe temperatures range from 20° C in the southeast to 27° C in the northwest.

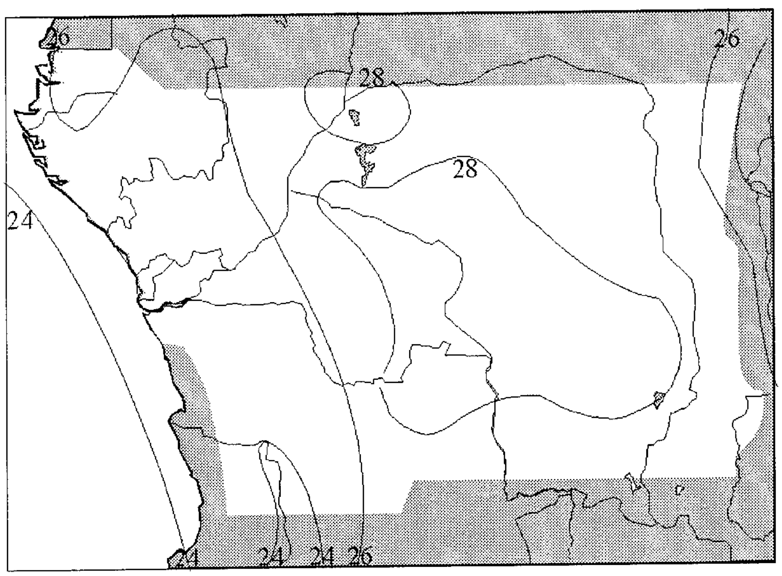


Figure 6-16. July Mean Maximum Temperatures (° C).

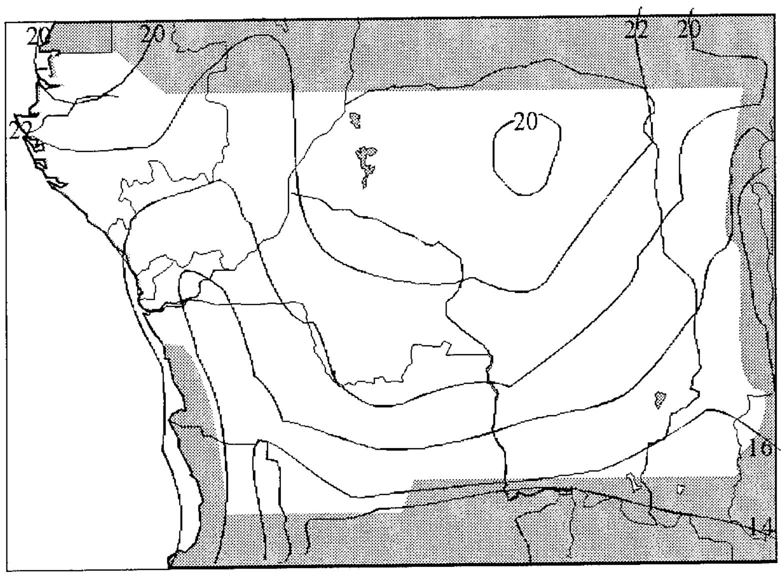
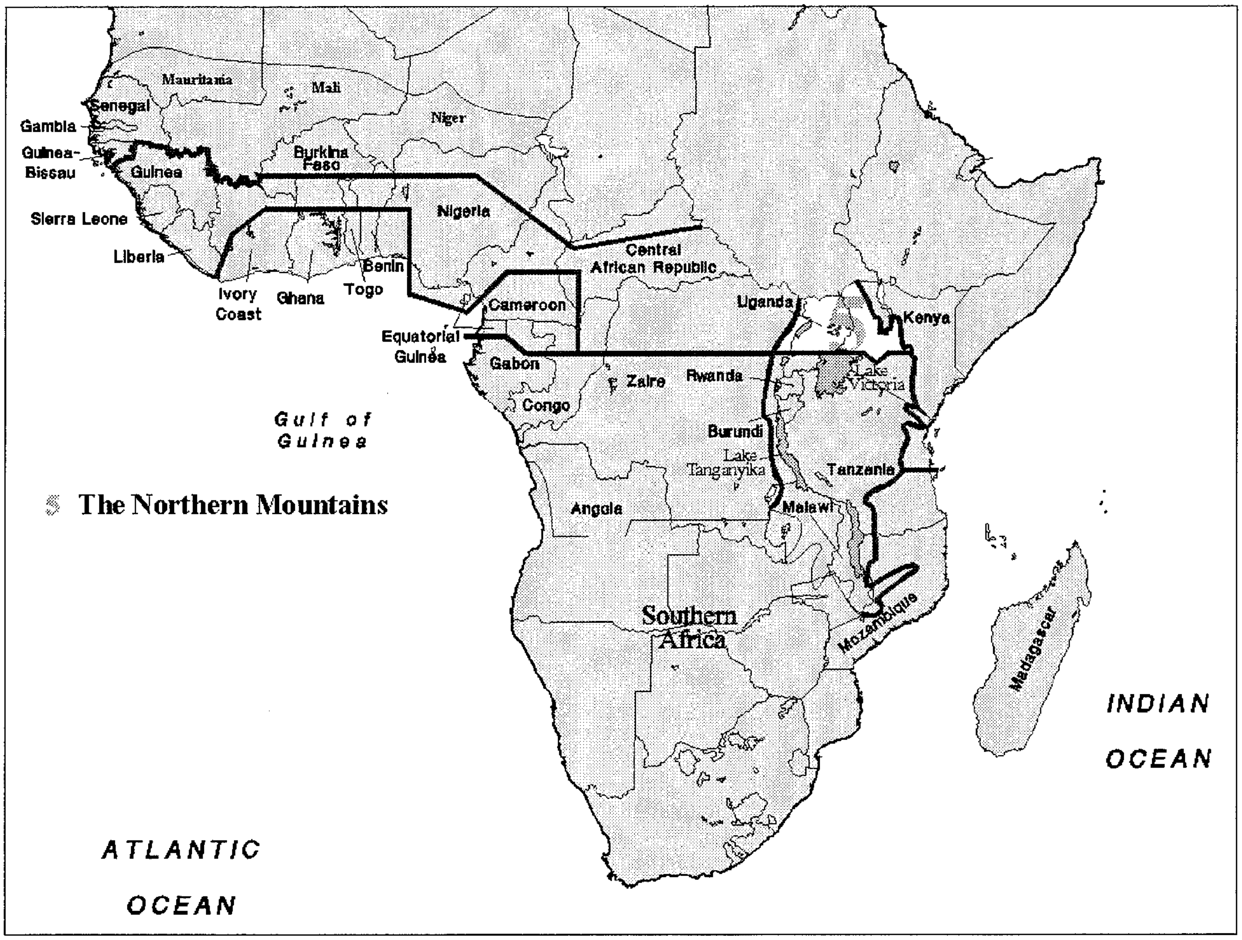


Figure 6-17. July Mean Minimum Temperatures (° C).

Chapter 7

THE NORTHERN MOUNTAINS

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) for the Northern Mountains, a climatic zone that comprises extreme eastern Zaire, all of Uganda north of Lake Victoria, and northwestern Kenya.



NORTHERN MOUNTAINS GEOGRAPHY

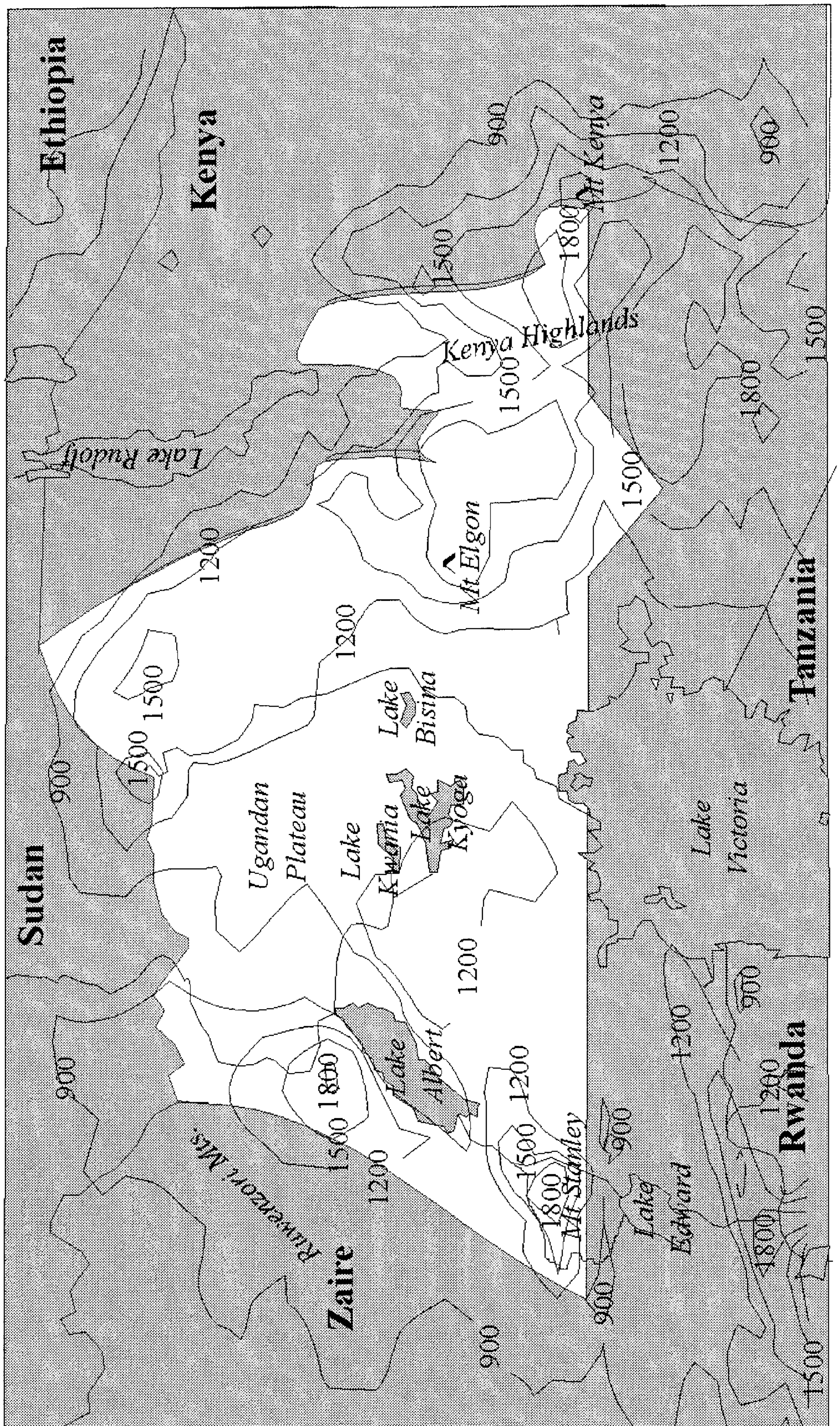


Figure 7-1. Topography of the Northern Mountains. Contours in meters.

NORTHERN MOUNTAINS GEOGRAPHY

Seasons. There is a short dry season (December through March) and a long wet season (April through November). A few local variations to these seasons are caused by terrain features such as Lake Victoria, Mount Stanley, and the mountains along the west side of the Great Rift.

Boundaries. This zone runs from the equator north to 4° N, and from 29° to 38° E. The western boundary is formed by the crest of the Ruwenzori Mountains. The northern boundary begins at 30.5° E and follows the Sudan-Uganda and Kenya-Sudan borders eastward to the 900-meter contour. The 1,500-meter contour forms the eastern boundary. The southern border runs westward across the Kenyan Highlands and the north shore of Lake Victoria to the slopes of the Great Rift Range just north of Lake Edward.

Major Terrain Features. The two features described below have a significant influence on the weather and climate of the Northern Mountains.

The Great African Rift System. The Rift itself lies along a line from Lake Albert to Lake Edward and southward. The Ruwenzori Mountains, west of the lakes, are dominated by Mount Stanley, which reaches 5,119 meters, the highest point in the zone. The eastern rift marks the start of the Kenya Highlands, which average well over 1,500 meters. They are dominated by Mt Elgon, another volcanic peak (4,321 meters), which straddles the Uganda-Kenya border just north of Lake Victoria. Southeastward from Mt Elgon, the Mau Escarpment separates the high terrain of western Kenya from Lake Victoria.

The Ugandan Plateau. A broad open plateau with isolated peaks covers most of Uganda eastward to a smaller rift on the Kenyan border. The plateau slopes gently downward from just north of Lake Victoria toward southern Sudan.

Rivers and Drainage Systems. Lake Victoria, the largest lake in Africa and one of the sources of the Nile River, also plays a major role in the zone's climate. Water from the lake drains via the Victoria Nile into Lake Kyoga and Lake Kwania in the central Plateau, thence to Lake Albert in the northern Rift. From Lake Albert, water drains via the Albert Nile north into Sudan. Numerous smaller lakes, the largest of which is Lake Kyoga, are found in southern Uganda about 75 miles north of Lake Victoria.

Vegetation. The lower slopes of the mountains on both sides of the Plateau once had extensive tropical rain forests, but most of these have been cleared by farmers, especially in the Kenya highlands east of Lake Victoria. The highest reaches of the mountains (above 4,300 meters) have permanent snow cover. Most of the Plateau, where not cultivated, is covered by grassy savannah.

MAJOR CLIMATIC CONTROLS OF THE NORTHERN MOUNTAINS

Elevation. Although not usually considered a climatic control, elevation is crucial here. Solar radiation is intense in this zone just north of the equator, but the high elevations moderate its effects. Plateau elevations range between 900 and 1,200 meters. The Albert Nile, however, located in the bottom of the Rift, drops to just over 600 meters at the Sudan frontier. East of Lake Victoria, the Kenyan Highlands average over 1,500 meters. Fresh outbreaks of hot and moist tropical air rarely reach the plateau because of the mountains on the west and east. As a result, climate is considerably more temperate than might otherwise be expected.

The Near Equatorial Trough (NET). Although the NET crosses the area twice a year (in April and December), it lies in the Great Rift on the western side of the region from December through April. The result is one long wet season (April through November) and a short dry season (December through March). Some local variations to these seasons are caused by Lake Victoria, Mount Stanley, and the Ruwenzori Mountains along the west side of the Rift.

Harmattan Winds (Northeast Monsoon). These dry northerly and northeasterly winds blow over most of the region during the dry season. Originating over the Sahara, their strength fluctuates depending upon passage of Mediterranean cold fronts with the associated upper troughs across northern Africa. Strongest winds occur after the upper trough has crossed the Red Sea. As might be expected, Harmattan winds bring clear skies, hot, dry air, and extensive dust below 1,500 to 2,100 meters.

Recurved Equatorial Westerlies. Although rare, these occur over the extreme northern portion of the Uganda Plateau during the height of the wet season whenever moist tropical Atlantic air penetrates this far east. Showers and lines of thunderstorms may occur near the Sudanese border during even rarer strong cases, during which a convergence line sets up between the recurved Atlantic air and southeasterlies from the Indian Ocean.

Land/lake Breezes. These are present on all the large lakes, but they are most pronounced near Lake Victoria. Because of its size and location, Lake Victoria has an especially active land/lake breeze that results in showers and thundershowers within 100 km of the lake all year long. Onset of the showers and thundershowers varies with the season. In the dry season, showers form over the lake and move onshore with the lake breeze in late morning and early afternoon. Convection persists until the lake breeze dies shortly after sunset. During the wet season, showers and thundershowers form during daylight hours from mid- to late morning over land. A shower or thundershower line often forms along the shoreline or just inland before dawn when the land breeze is at its strongest. The convergence between the land breeze and the steady onshore southeasterly trades acts as the trigger. For an expanded treatment of the general land/lake breeze phenomenon, see Chapter 2, "Mesoscale and Local Effects."

Mountain-Valley Breezes. Although they are found near all the mountain ranges, they are strongest along the eastern shore of Lake Victoria (Mau Escarpment and Mt Elgon), the western shore of Lake Albert, and the northern shore of Lake Edward. These breezes are responsible for enhancing or retarding the formation of (and fixing the location of) showers and thundershowers near the lakes. See Chapter 2, "Mesoscale and Local Effects," for a complete discussion.

General Weather. With the NET lying over the Great Rift, winds are generally dry except where they are controlled by lake breezes. Harmattan winds bring in patchy amounts of dust aloft. Land/lake breezes and mountain-valley winds dominate local weather except during sustained Harmattan conditions.

On very rare occasions, a temperate-zone upper-level trough extends far enough south to affect the northern portion of the zone. Such troughs almost always result in active cyclogenesis over the central and northern Sudan; the resulting low moves into the Red Sea and across northern Saudi Arabia. In the Northern Mountains zone, middle and high clouds form ahead of and with the trough; there are patchy showers and thundershowers with the trough. Fresh Harmattan winds with extensive suspended dust follow trough passages, which also result in snowfalls over the highest peaks. The snow normally falls above 4,000 meters, but sometimes as low as 3,500 meters for brief periods.

Sky Cover. Except for the diurnal cumulus cycle near the lakes and over the mountains, cloudiness is not much of a problem; most is of the low and middle variety, with some high cirriform ceilings. Near lakes (especially near Lake Victoria), cloud lines with isolated showers and thundershowers form offshore over water before dawn and move onshore as the lake breeze becomes strong enough. Ceilings with these shower lines are normally above 1,000 feet, but they may drop briefly to less than 500 feet in shower cores. As shown in Figure 7-2, ceilings over the plains are uncommon; in mid- to late-morning, however, patchy low clouds formed by heating temporarily reach 60 to 70 percent coverage before dissipating. Ceilings occur with greater frequency only when local effects associated with moisture sources are present. Note that only mountain locations (Kasese and Nakuru in Figure 7-3 are examples) have ceilings below 3,000 feet with any reasonable frequency. Even here, they are strictly controlled by the diurnal cycle. Entebbe shows the effects of irregular synoptic winds combined with the land/lake breeze. Only in March, as the NET moves close to the northern Lake Victoria shore, does an afternoon low-cloud ceiling frequency begin to appear.

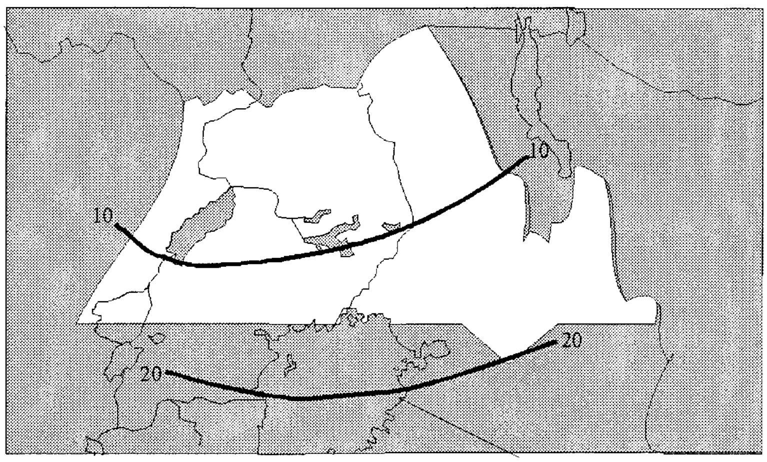


Figure 7-2. January Percent Frequencies of Ceilings.

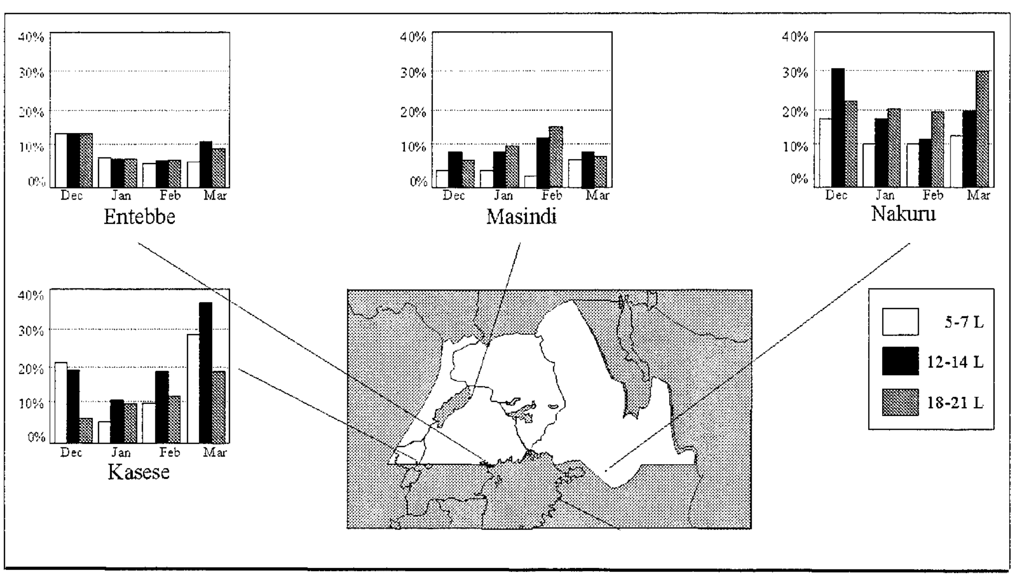


Figure 7-3. Dry-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibilities. Visibilities away from immediate lake shores, mountain basins, and river valleys are excellent except when a fresh Harmattan outbreak moves into the zone. There are some smoke and haze restrictions near dawn and near manufacturing and mining facilities. Visibilities are frequently below 4,800 meters near lakes and in mountain basins. Fog banks form offshore over Lakes Victoria and Albert near the end of the season, then drift onshore in late afternoon and evening; land breezes move the fog back offshore by late evening. The fairly high frequency of afternoon and evening fog at Masindi on the Lake Albert shore reflects local terrain/lake peculiarities.

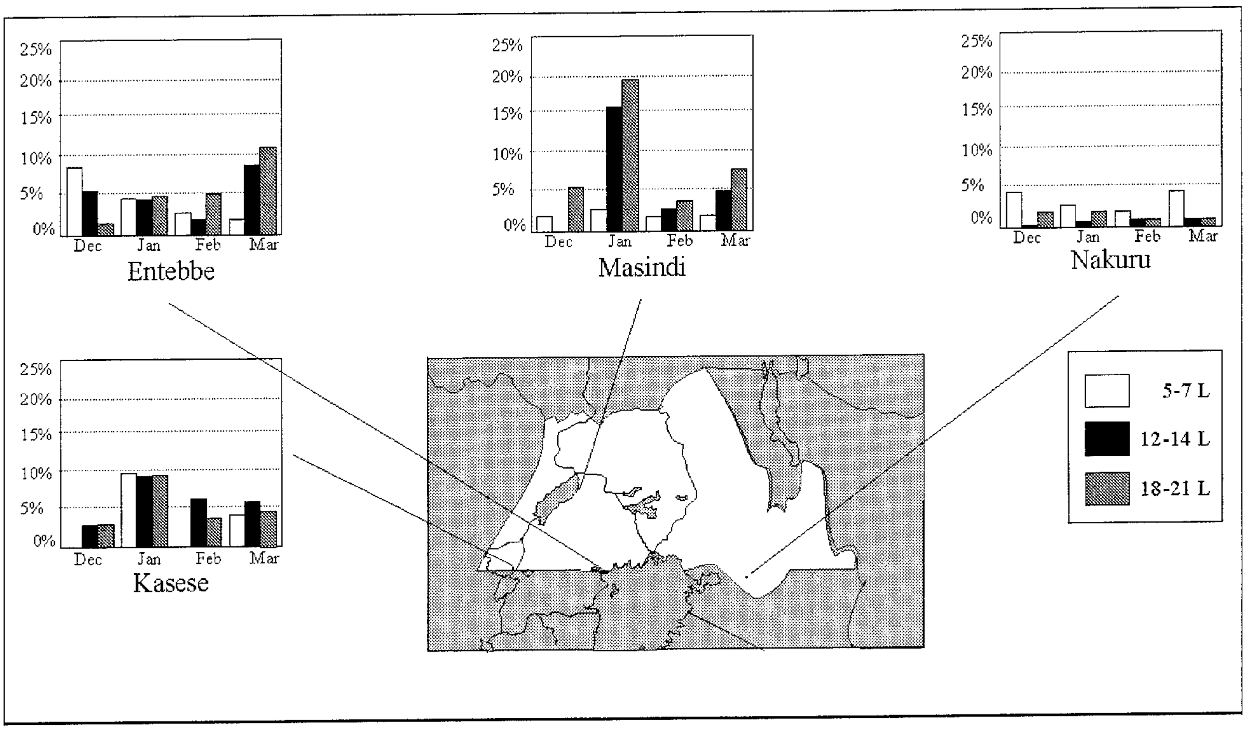


Figure 7-4. Dry-Season Percent Frequencies of Visibilities Below 4,800 Meters.

Surface Winds. Most stations are dominated by local diurnal wind circulations. Land/lake breeze circulations are evident at Entebbe and Masindi, while mountain-valley breezes control Kasese winds. Only Nakuru clearly shows the effects of the Harmattan winds and the northeast monsoon. Masindi's northerly and southerly winds may also partly reflect oscillations in the NET. Winds are light across the zone; only at Entebbe (with its Lake Victoria exposure) and Nakuru in the Kenya highlands, are there significant frequencies of winds above 10 knots. There are no upper-air reporting stations in this zone; see Chapters 6 and 8 for upper-air wind roses in neighboring zones.

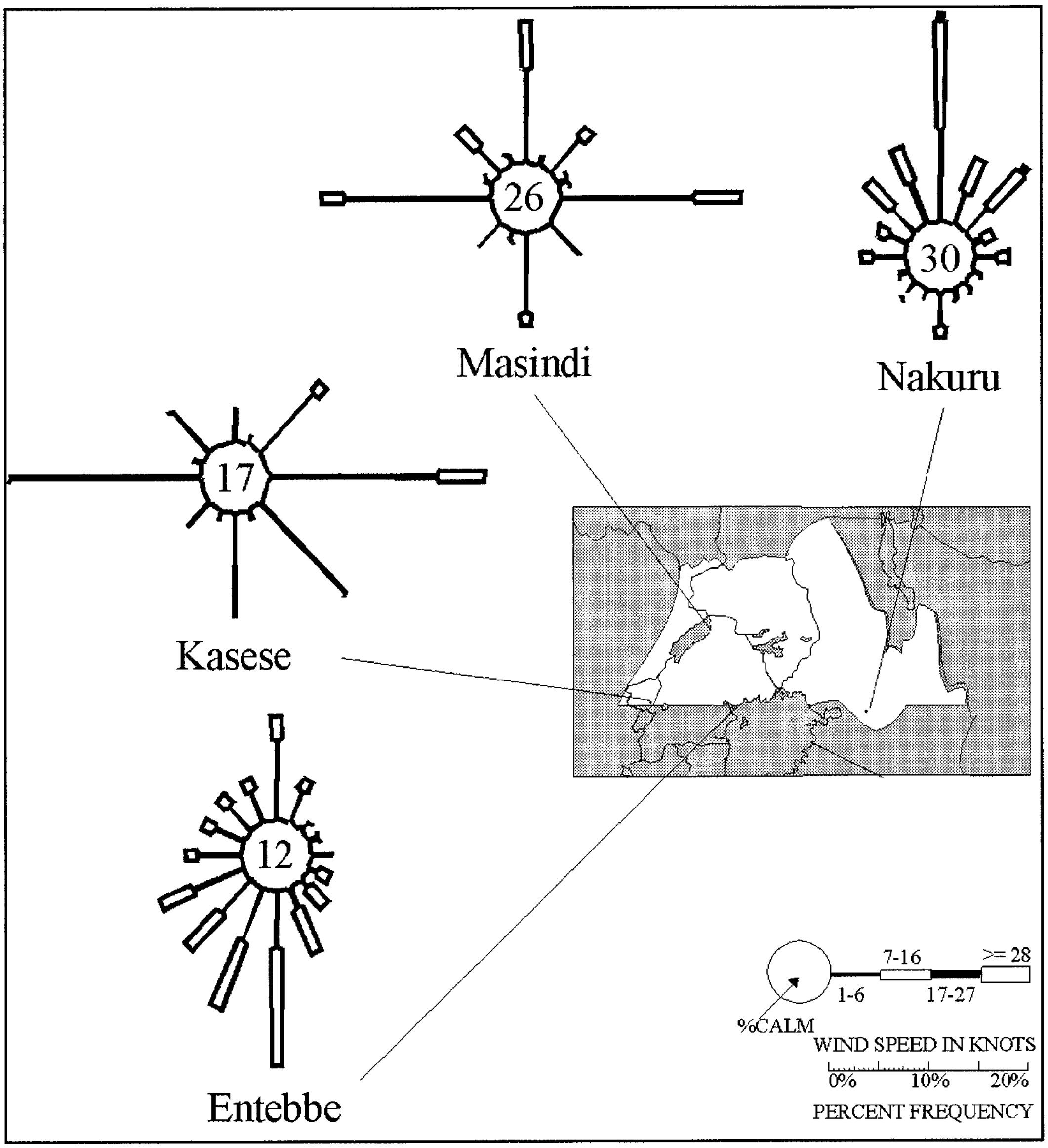


Figure 7-5. February Surface Wind Roses.

Precipitation. Except for widely scattered Uganda Plateau showers, precipitation amounts reflect the distribution of moisture sources. The greatest February precipitation occurs within 50 km of Lake Victoria. Distributions are similar during the rest of the dry season.

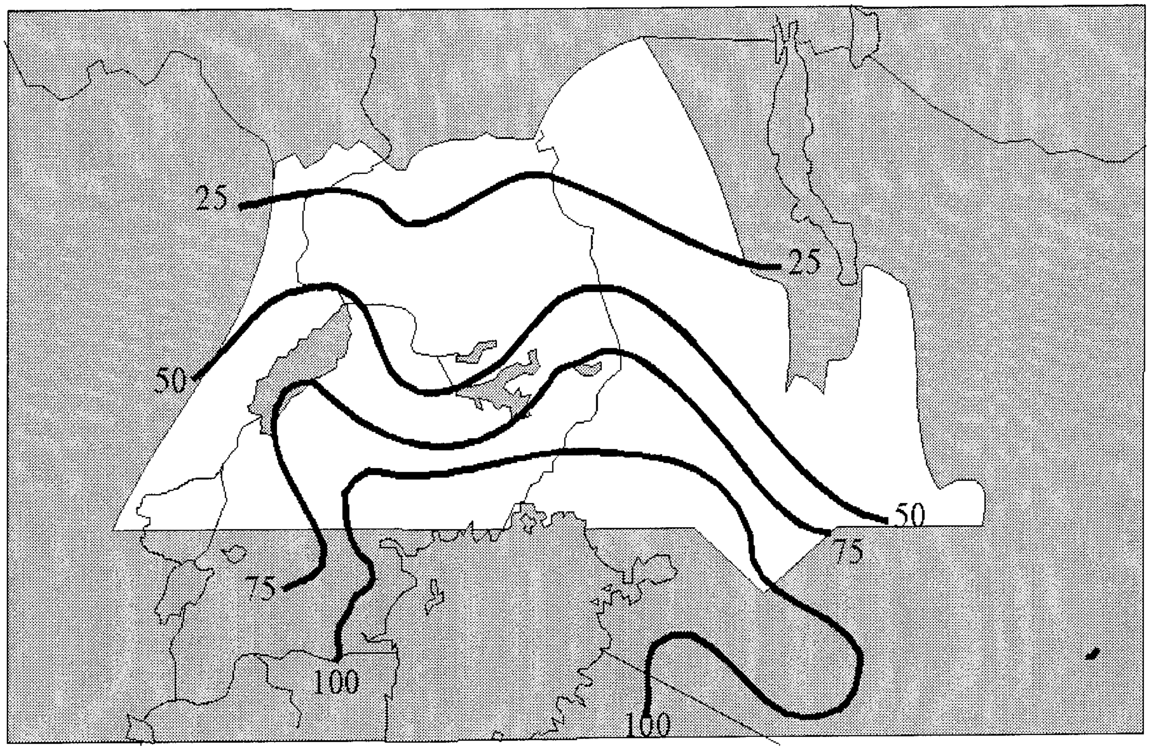


Figure 7-6. February Mean Precipitation (mm).

Thunderstorms. Thunderstorms are uncommon except near the Great Rift lakes and Lake Victoria. The relatively strong land/lake breeze at Entebbe, representative of the entire northern Lake Victoria shore, results in shower and thundershower frequencies more than twice those at other locations. Strong insolation, combined with ready supplies of moisture near the lakes, results in thunderstorm tops that reach 40,000 feet. Hail reaches the surface on 1 day in 5 over the higher mountains and east of the Mau Escarpment. Most thunderstorms form near the lakes during late morning and early afternoon, but over the higher mountains, most occur in the afternoon. The strongest storms form in late afternoon.

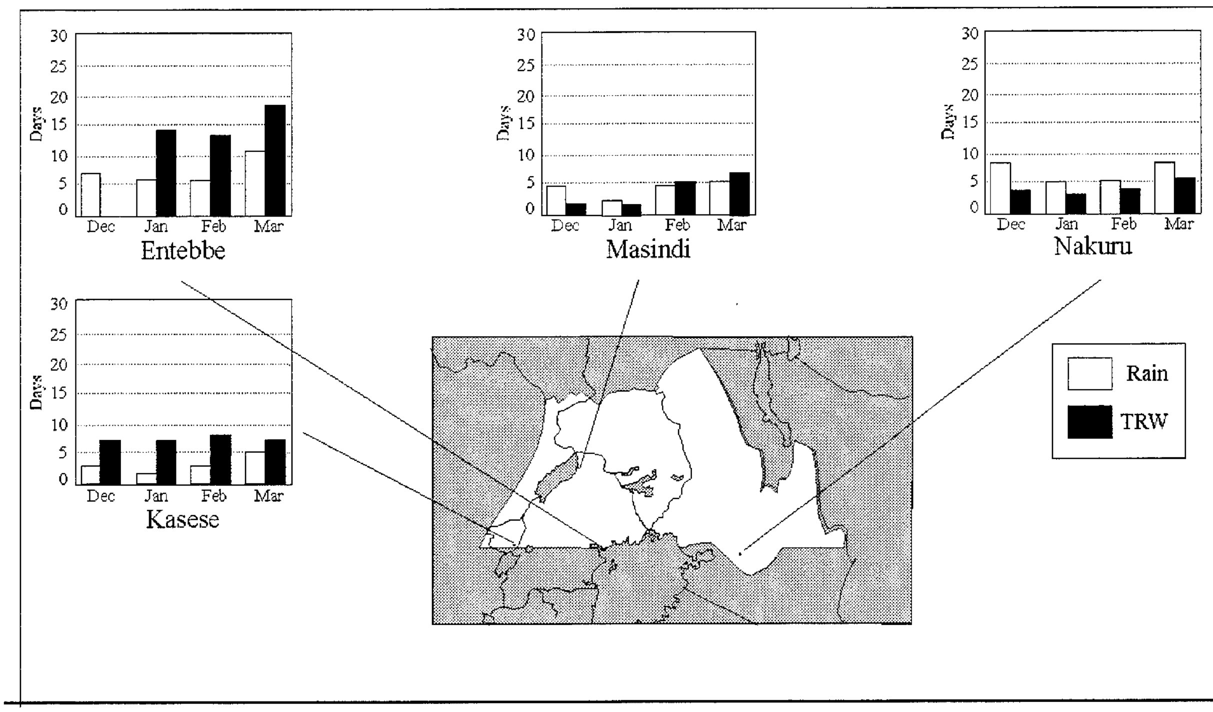


Figure 7-7. Dry-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. As noted earlier, temperature in the Northern mountains is a function of altitude. Nighttime temperatures fall below 0° C above 3,500 to 4,000 meters routinely. Conversely, both maximum and minimum temperatures over the Uganda Plateau show steady increases toward lower, dryer areas, with the highest near Sudan. Wet-bulb globe temperatures are near 28° C.

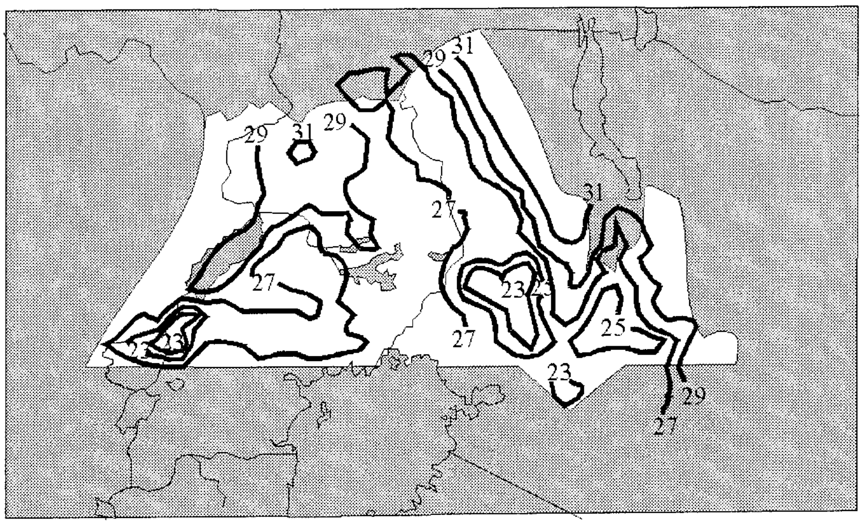


Figure 7-8a. January Mean Maximum Temperatures.

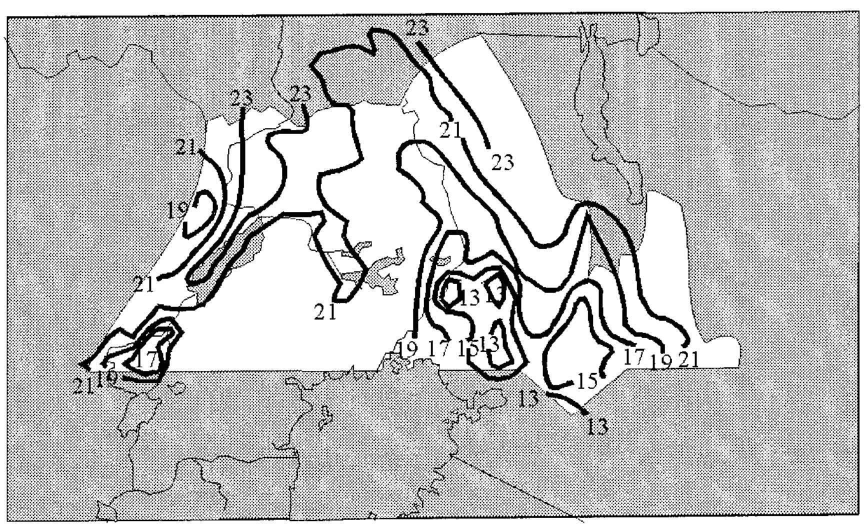


Figure 7-8b. January Mean Minimum Temperatures.

Other Hazards. The persistent suspended dust aloft associated with Harmattan winds can reduce in-flight visibilities to less than 4,800 meters. Conditions are worst when flying east shortly after dawn and west shortly before sunset, when slant-range visibilities can be as low as 2,000 meters.

Fog banks that form over lakes or in river valleys at night may move over airports along immediate shorelines with little warning; although shallow, they can reduce visibilities to below 800 meters. Unpaved roads are temporarily impassable immediately after heavy showers or thundershowers. Flash floods are rare but possible.

General Weather. With the NET lying well north of the region, southeasterly winds bring in a steady supply of moist, unstable Indian Ocean air. This, combined with the terrain, the lake effect, and the occasional penetration of equatorial westerlies into the northern Ugandan Plateau, results in widespread rain and thundershowers. Low clouds are normally a mixture of stratiform and cumuliform, but by mid-morning, convective clouds predominate. Middle and high clouds are usually associated with thunderstorms or deep convection. Extensively layered clouds, however, are uncommon except near mountains and organized thunderstorm lines or complexes, where the deep convection acts as "cloud factories," with resultant widespread layered middle and high clouds.

From June through September, the equatorial westerlies are occasionally deflected southeastward out of Sudan and extreme northern Zaire into northern Uganda. Such intrusions normally occur with an eastward "pulse" of the Congo Air Boundary, the convergence line between recurved South Atlantic Equatorial Westerlies and the southeasterly Indian ocean trade winds. Such intrusions result in the most widespread showers, thundershowers, and even steady rain, of the entire wet season. Often lasting several days, these events result in widespread flooding.

Although it was formerly thought that West African squall lines originated in northern Uganda and/or northwestern Kenya, it is now known that they form north of the Northern Mountains zone. The misconception was apparently based on observations that thunderstorm lines/areas form along the convergence zone between a retreating Equatorial Westerly event and advancing Indian Ocean southeasterlies.

Sky Cover. The diurnal cumulus cycle, enhanced near the lakes and over the mountains, is reflected in the high frequencies of cloud cover and ceilings shown in Figures 7-9 and 7-10. Although low ceilings are common, the frequencies of middle and high ceilings are also considerable.

By late morning, shower and thundershower lines often form immediately downwind of rivers. Near lakes, and especially near Lake Victoria, cloud lines with isolated showers and thundershowers form just offshore over water immediately after dawn, then move onshore. By mid-morning, they combine with showers and thundershowers forming along the leading edge of the lake breeze. Such systems can move over 100 km inland from Lake Victoria before dissipating. Ceilings in these shower lines are normally above 500 feet, but they can drop briefly below 100 feet in shower cores.

Ceilings over the plains, as can be seen in Figure 7-9, decrease slowly toward the northwest. Frequencies remain high over the Mt Elgon and Mau Escarpment areas, mainly because of the Lake Victoria land/lake breeze system that now opposes the southeasterly Indian Ocean trade winds.

Note that the diurnal variation of ceilings below 3,000 feet over mountainous areas is not the same as near lakes, where low ceilings peak in early afternoon throughout the season. Over the mountains, peak frequencies occur either in early evening or early morning depending on terrain. Nocturnal showers and their low ceilings are confined to areas immediately upwind and offshore of lake fronts, or to areas where two mountain winds meet. These diurnal variations enhance cloud systems associated with synoptic scale convergence lines, especially in the north or along the Congo Air Boundary.

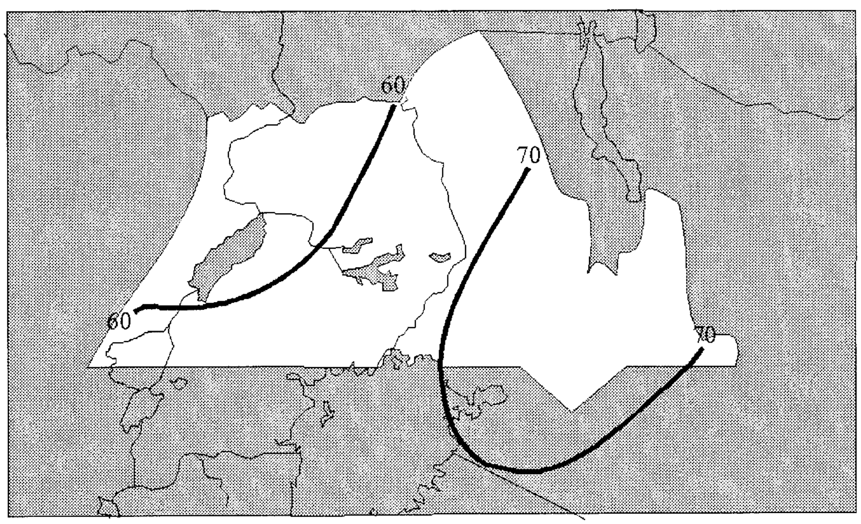


Figure 7-9. July Percent Frequencies of Ceilings.

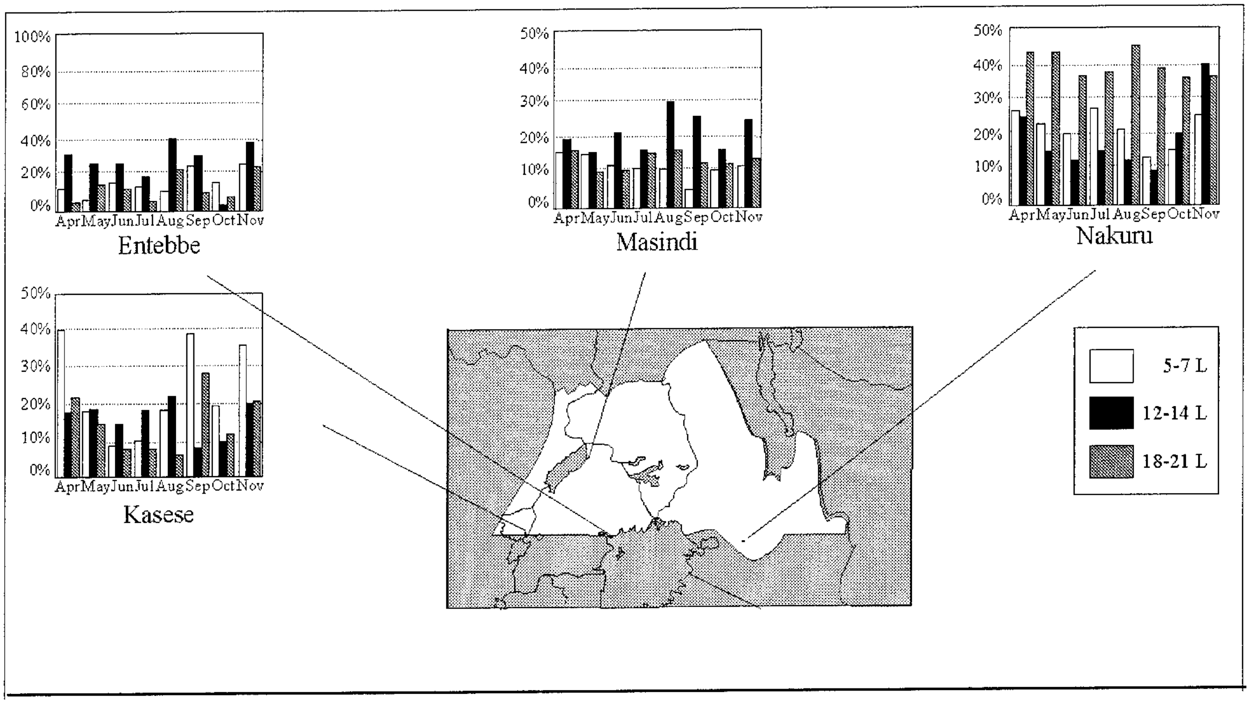


Figure 7-10. Wet-Season Percent Frequencies of Ceilings Below 3,000 feet.

Visibilities. Mountain valley, river valley, and inland locations often have patchy early morning ground fog that may be dense enough to briefly restrict visibility below 4,800 meters just before sunrise and for an hour or two afterward. Afternoon and early evening visibilities are usually reduced by heavy rain showers, often to less than 800 meters.

Note that, as flow patterns shift with the advance and retreat of the NET, the favored times for reduced visibility in the Great Rift, over the Uganda Plateau, and along the north shore of Lake Victoria also shift. Only over the Mau Escarpment does the diurnal time pattern remain constant throughout the wet season.

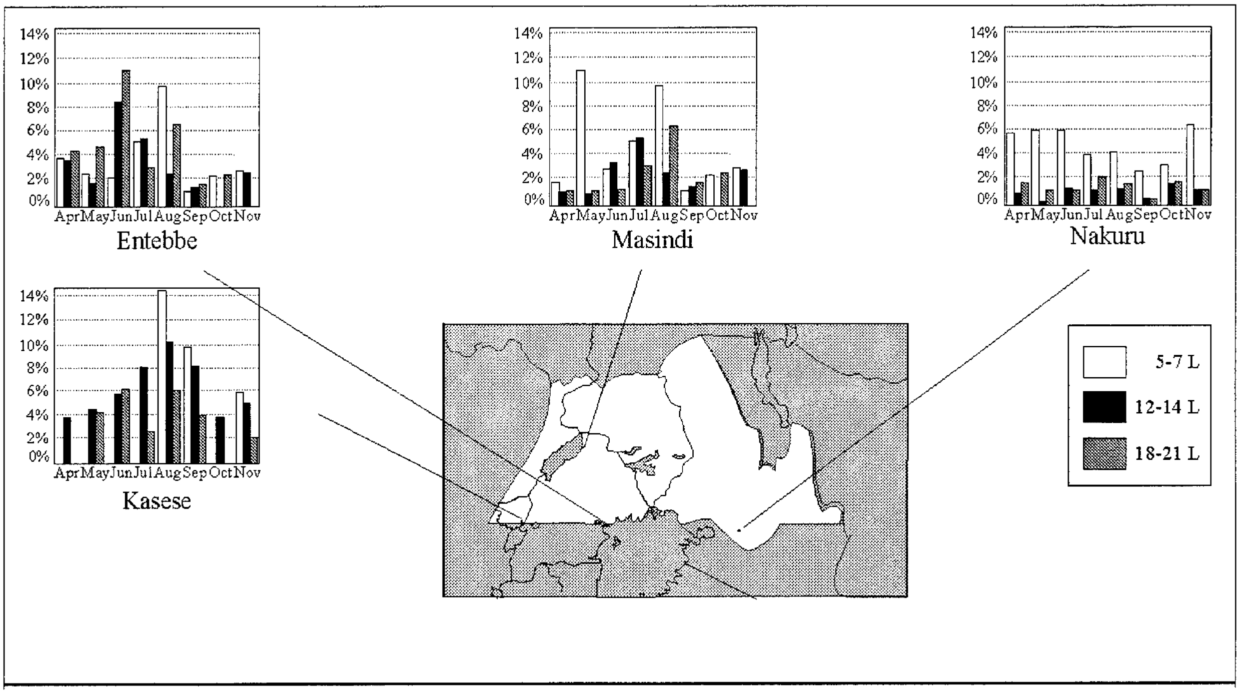


Figure 7-11. Wet-Season Percent Frequencies of Visibilities Below 4,800 Meters.

Surface Winds. Most stations are still heavily influenced by local diurnal wind circulations; Entebbe and Kasese are examples. Over the Mau Escarpment, however, the prevailing southeasterly Indian Ocean trades are obvious. Much of the variation at Masindi is from a combination of equatorial westerlies and mountain-valley breezes. Uganda Plateau winds show net southerly to southeasterly flow after the subtraction of diurnal effects. This flow reinforces lake breezes at Entebbe. Significantly, the strongest winds at both Nakuru and Entebbe are from southeast to south—the only directions from which mean speeds exceed 17 knots. There are no upper-air reporting stations in the zone; see Chapters 6 and 8 for upper-level wind roses in neighboring zones.

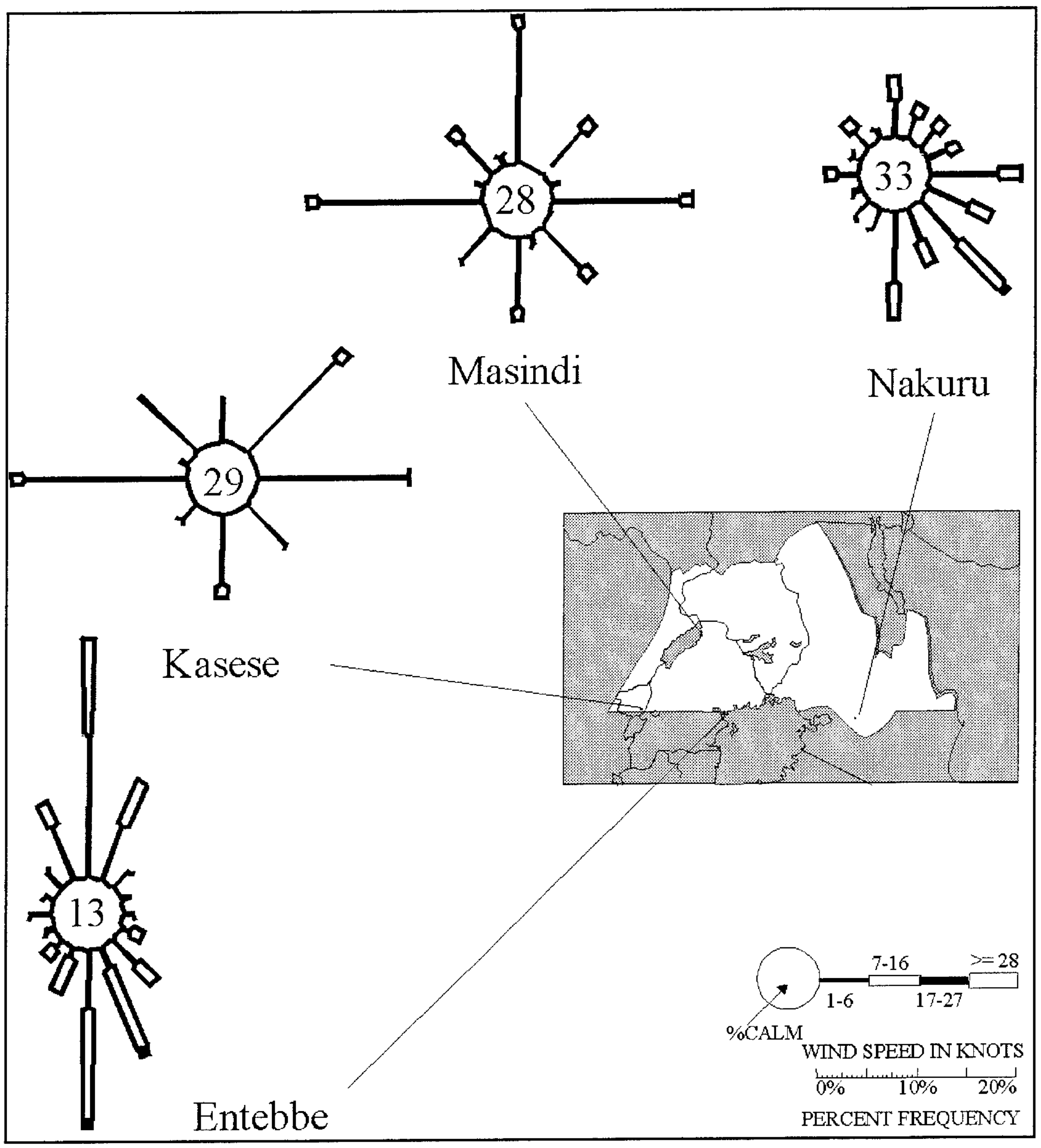


Figure 7-12. August Surface Wind Roses.

Precipitation. Rainfall at the height of the wet season is more than 6 to 8 times heavier than during the dry season. Precipitation patterns reflect the combined influences of the mountains and lakes.

Note the relatively low precipitation amounts over the Great Rift and immediately downwind of Lake Victoria. Similar patterns are observed worldwide under these land/water and orographic conditions .

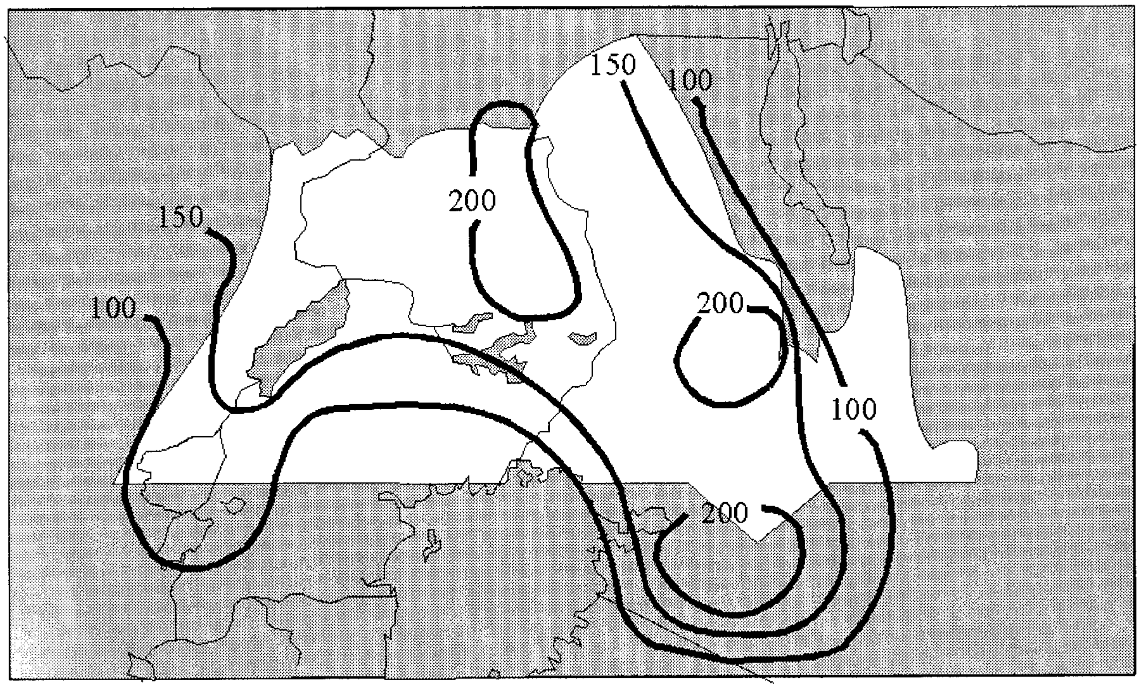


Figure 7-13. August Mean Precipitation (mm).

Thunderstorms. Showers and thundershowers occur once every 1 ½ to 2 days over most of the region. Precipitation falls near Lake Victoria almost every day. Thunderstorms are at least as common as showers, and often more common. In view of the intense solar radiation, moderately unstable air, and ample moisture, this should not be a surprise. Thunderstorm tops can, and often do, exceed 50,000 feet. Tops are highest in mid- to late afternoon.

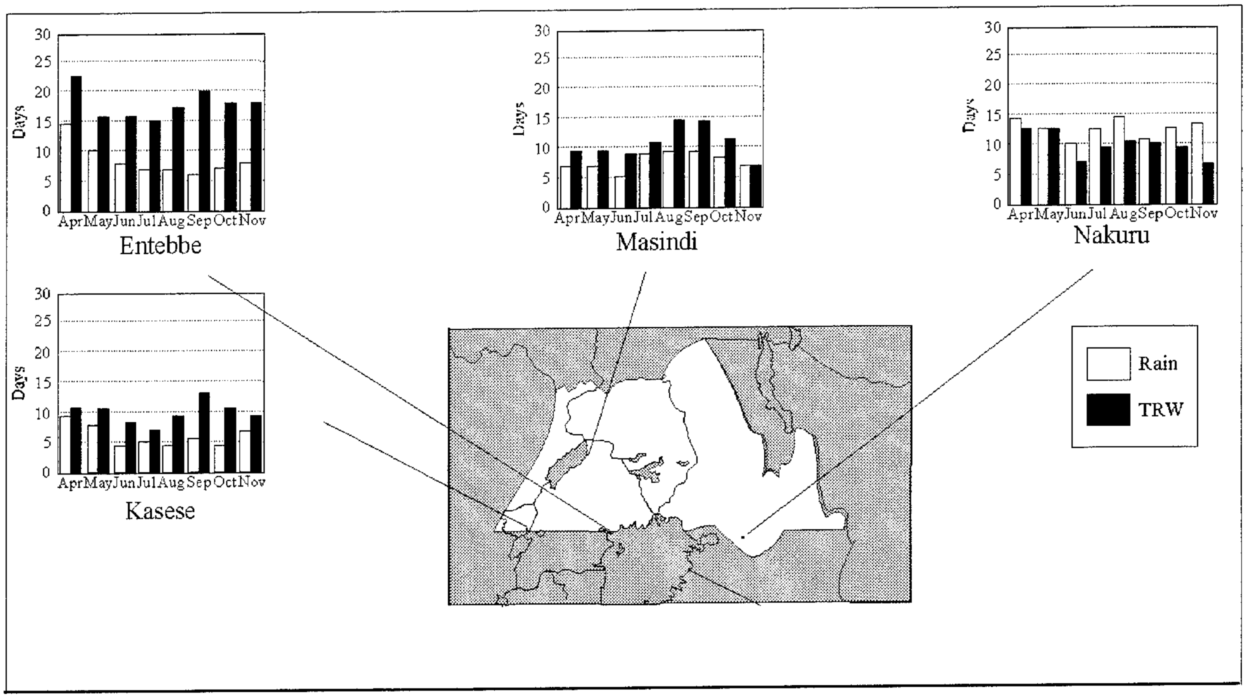


Figure 7-14. Wet-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Wet-season temperatures are influenced by cloud cover as well as by altitude. The maximum and minimum temperatures shown in Figures 7-15a and b reflect this, even though the effects of the higher mountains are obscured by the scale and lack of reporting stations.

Nighttime temperatures fall below 0° C above 4,500 meters. Maximum and minimum temperatures over the Uganda Plateau show little latitudinal variation; the effects of increasing cloud cover tend to cancel the temperature increases that normally occur at lower latitudes. Wet-bulb globe temperatures are near 25° C.

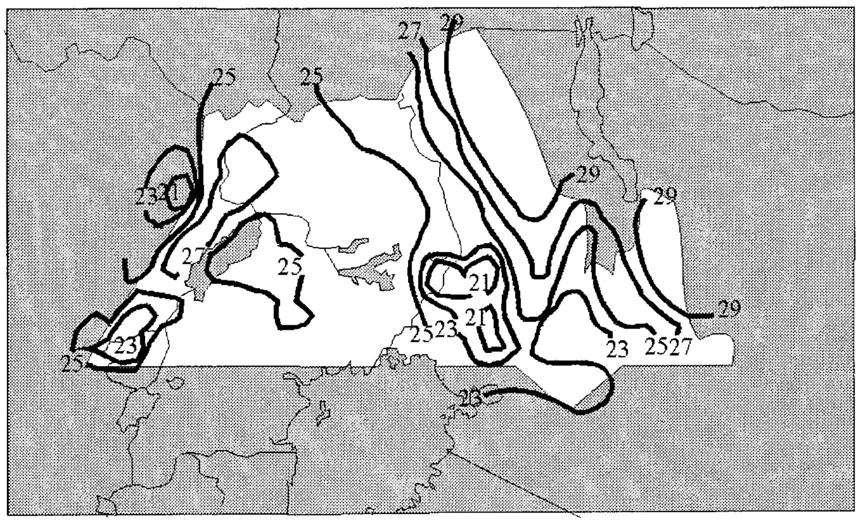


Figure 7-15a. August Mean Maximum Temperatures.

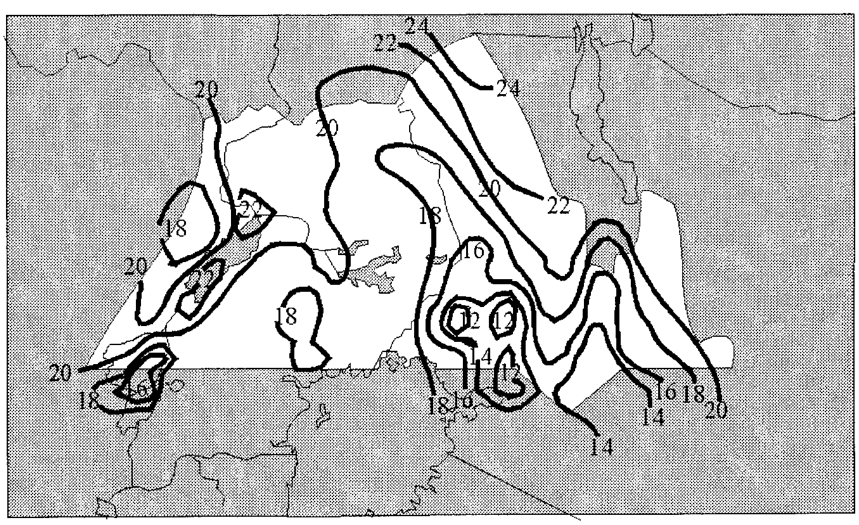


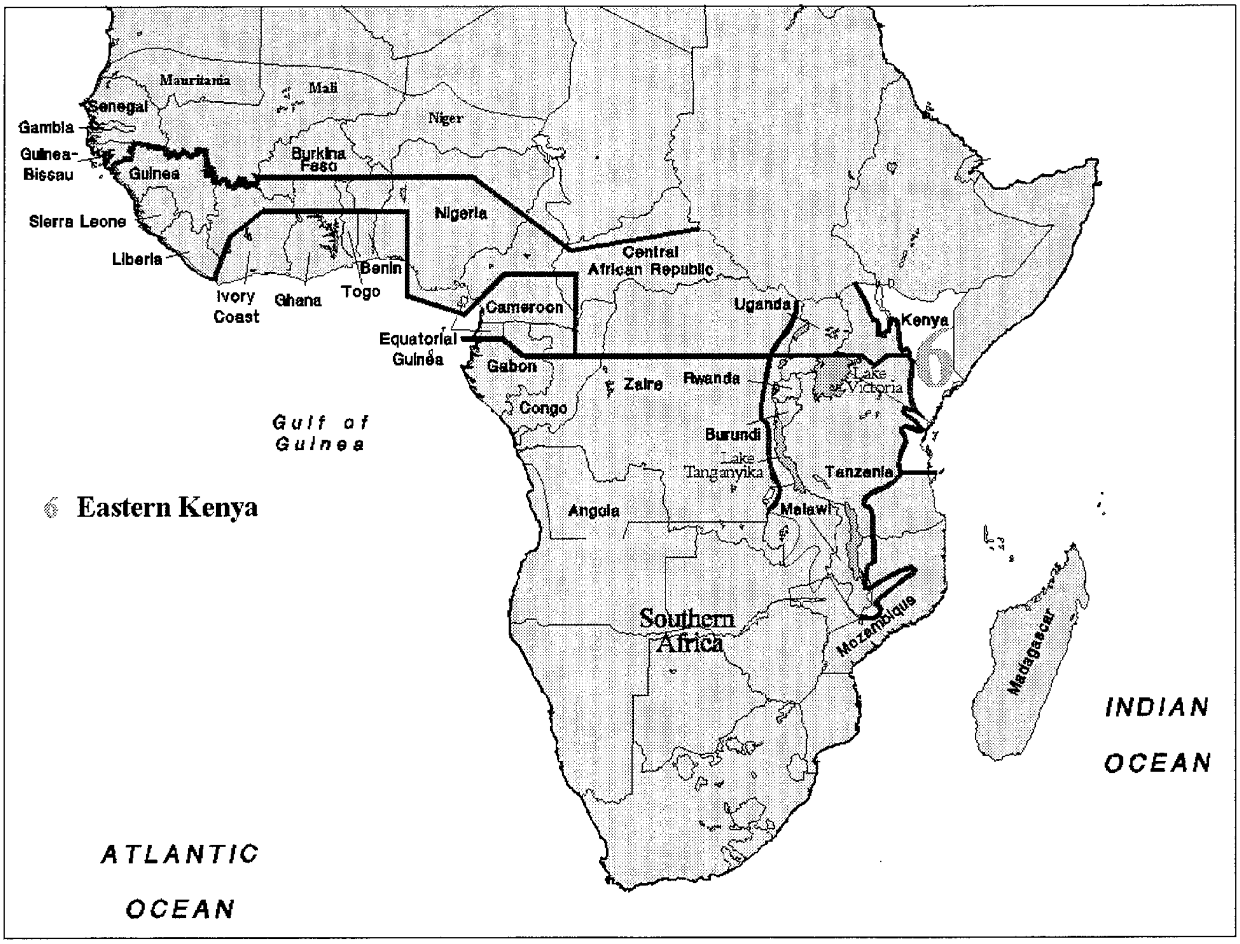
Figure 7-15b. August Mean Minimum Temperatures.

Other Hazards. Thunderstorms bring their usual turbulence, icing, hail, gusty winds, and torrential rainshowers, along with obscured terrain, mud, and flooding. Hail falls on nearly 1 day in 3 over the Mau Escarpment. Patchy nocturnal fog banks that form over lakes or in river valleys at night may move over airports along immediate shorelines with little warning. Although shallow, these fog banks can reduce visibilities to below 800 meters. With heavy rainfall, unpaved roads become bogs; streams rapidly rise over their banks and cause extensive flooding. Flash floods can occur in and near mountains.

Chapter 8

EASTERN KENYA

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) of Eastern Kenya, a relatively small climatic zone that lies along the equator adjacent to the Indian Ocean in the east and the Kenyan Highlands in the west. It comprises northeastern Kenya and a small coastal portion of northeastern Tanzania.



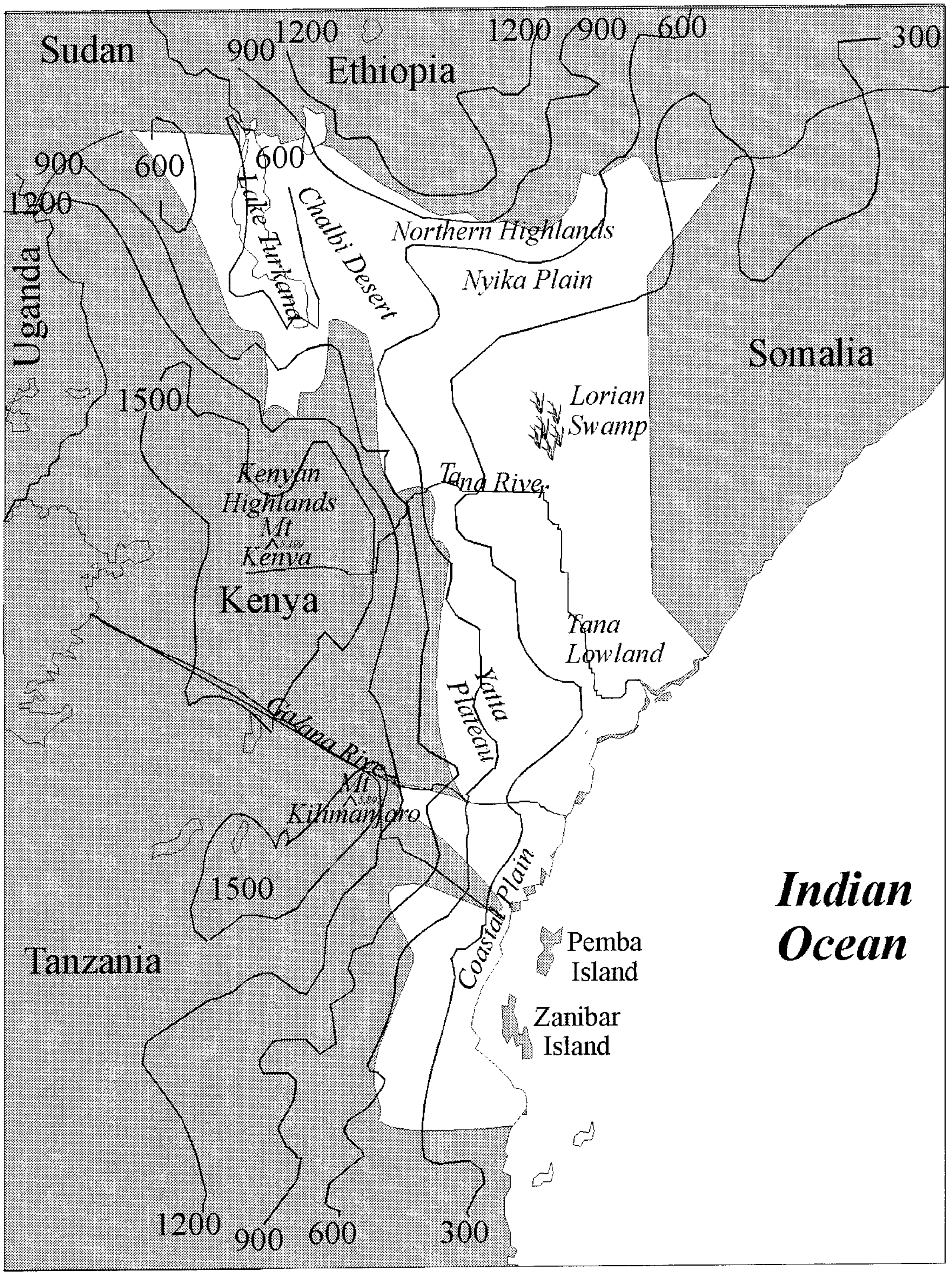


Figure 8-1. The Topography of Eastern Kenya.

EASTERN KENYA GEOGRAPHY

Seasons. There are two wet seasons and two dry seasons in this zone. The wet seasons, dominated by the Northeast Monsoon, run from March to May and from October to December. The dry seasons (dominated by the Southeast Monsoon) run from January to February and from June to September.

Boundaries. The western boundary is marked by the 900-meter contour, while the southern boundary is defined by the dual wet and dry seasons. The region is bordered to the north by Sudan and Ethiopia; to the east, by Somalia and the Indian Ocean. The southern geographical boundary is formed by the 7° S parallel that extends from the Indian Ocean to the 900-meter contour of the Kenyan Highlands. The western boundary follows the 900-meter contour northward as it meanders to the Sudanese border.

Major Terrain Features. Terrain rises very gradually throughout the region, with steeper ground found within the narrow coastal strip along the Kenyan/Tanzanian border, the northern highlands, and isolated mountains such as those at Marsabit.

The Indian Ocean coast, about 750 kilometers long, contains many bays, inlets, and river mouths. The coastline is mostly coral rock and light sandy soil. There are several islands off the coast, including Zanzibar and Pemba. In the south, the coastal plain stretches to the foothills, then narrows near the Kenyan/Tanzanian border to a strip less than 10 miles wide. To the north, the coastal plain broadens, forming the 100-mile-wide Tana Lowlands and the Yatta Plateau, a series of steppes and small plateaus that gradually rise to the west.

The vast Nyika ("wilderness") Plain, which covers most of the northern part of the zone, includes Lake Turkana, the Lorian Swamp, and the Chalbi Desert. It consists of a series of plains and depressions, interspersed with unusual elevated formations. The Northern Highlands that run along the northern border of the zone are actually the southward extension of the Ethiopian Highlands.

Rivers and Drainage. The region is drained by a network of intermittent small rivers and streams, all with marked seasonal changes in flow. The two most important rivers are the Tana and Galana. Both rise in the eastern highlands and flow southeast into the Indian Ocean. Lake Turkana, at an elevation of 375 meters, lies in the northwestern portion of the region and extends into Ethiopia. The lake is 248 kilometers long and only 16-32 kilometers wide. Rocky volcanic outcroppings dot the eastern and southern shores; sand dunes, sandspits, and mud flats are found along the lower western and northern shores.

Vegetation. Along the coast, mangrove swamps line creeks and river valleys. Coconut woodlands and brush are common. Clove and coconut estates cover Zanzibar and Pemba Islands. Sisal and cashew nut plantations are found on the mainland. In the interior, low trees and grass are found scattered through a mostly arid thornbush plain.

MAJOR CLIMATIC CONTROLS OF EASTERN KENYA

The Northeasterly and Southeasterly Monsoon flow, along with the movement of the NET, are the primary climatic controls. Aloft, the region is under the influence of the easterly trade winds. The Indian Ocean provides moisture for the region and causes land/sea breezes along the coast.

Both monsoonal flows average only 2 km in depth; both are capped by inversions and dry subsiding air. These conditions, combined with divergent flow at the surface, create two dry seasons that are especially dry in the interior. The shorter of these two dry seasons occurs in January and February, while a longer one runs from June through September.

Since the region is at the equator, seasonal temperature variations are slight. Higher elevations are naturally cooler than coastal areas. Diurnal temperature variations are larger in the interior than near the coast, where temperatures are highest and humidities are extremely high. Humidity decreases inland, where dry conditions prevail most of the year.

Migratory synoptic systems seldom affect the region, but as the NET moves across the area during transition seasons, thunderstorms, showers, and continuous rain occur. A belt of greater rainfall (1,000 to 1,200 mm annually) runs north to south from about Malindi to Dar es Salaam. This wet belt extends inland a short distance, with precipitation amounts increasing around areas of higher elevation. The plains and steppes of the interior average far less rainfall, with annual means from 127 to 254 mm. Isolated mountains get more rainfall due to orographic lifting. For example, mean annual rainfall at Marsabit and the highlands along the Sudanese/ Ethiopian border is about 780 mm.

Marsabit (and, to a lesser extent, Garissa) experiences the effects of the Turkana Channel Jet described in Chapter 2. At Marsabit, winds are southeasterly the entire year, resulting in orographic clouds and fog. Garissa, along the Tana River and one of the hottest locations in the region, has a high percentage of clouds as a result of the stronger southeasterly flow aloft that brings Indian Ocean moisture. Elsewhere, wind speeds are about 6 knots. Speeds on the coast are highest around 1600L; in the interior, the strongest winds are recorded at about 0900L.

General Weather. The Northeast Monsoon produces a short, 2-month dry season as northeasterly flow from the Arabian High advects dry air into the region. Divergence occurs as northeasterly flow is split in two directions: toward the thermal trough in the Great Rift Valley and toward the Mozambique Channel Trough to the south. Along the coast, the air modified by its longer movement over the northern Indian Ocean is wetter and slightly less stable, resulting in enhanced cloudiness. On occasion, convergence lines develop in the northern Indian Ocean in response to surges in the monsoonal flow (stronger northerly flow meeting weaker northeasterly flow); these lines produce showers that move to the coast. Northeast Monsoon (dry-season) weather is usually hot and humid, becoming increasingly unpleasant over the course of the season. Conditions are most uncomfortable just before the main wet season, as high humidity and weak surface winds dominate. The interior is usually hot, dry, and clear, with occasional sandstorms, brushfires, and very isolated rainshowers or thunderstorms. Tropical cyclones to the southeast of the region can cause middle to high cloudiness in the south. On very rare occasions, tropical cyclones cause gale-force winds at Dar Es Salaam. Cyclones can force the NET to surge northward, producing weather more typical of the wet season.

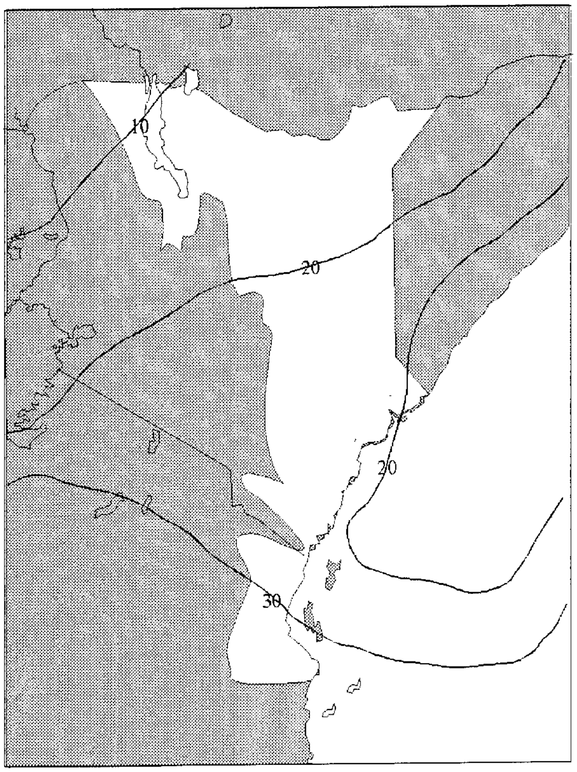


Figure 8-2. Secondary Dry Season Percent Frequencies of Ceilings.

Sky Cover depends on the proximity of moisture sources, topography, and elevation. As shown in Figure 8-2, cloudiness increases southward toward the seasonal position of the NET. In the interior, low-level cloudiness is generally least in the morning but increasing by afternoon. Near the coast (or near rivers), the reverse is true.

Most dry-season cloudiness is scattered fair-weather cumulus that forms in late morning. Base are 2,000 feet in the interior. Tops are usually only 3,000-4,000 feet. Nighttime and morning cloudiness also forms along the northern coast, where warmer water temperatures produce cumulus clouds that drift onshore, then dissipate during the day.

Ceilings below 1,000 feet are rare, and last only 1-2 hours. Morning stratus or stratocumulus can form in low-lying, marshy areas such as the Lorian Swamp, but they usually either lift to become cumulus or burn off rapidly after sunrise.

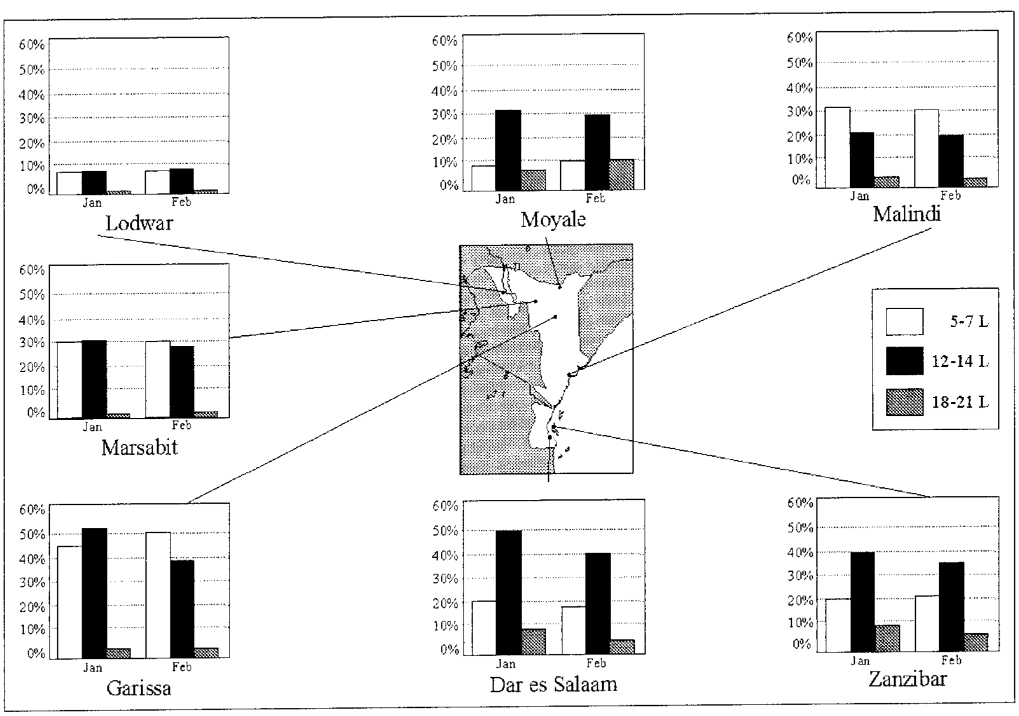


Figure 8-3. Secondary Dry Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility in the interior is occasionally restricted by fog or blowing dust and sand, but it rarely falls below 1,600 meters. The high dew points of the tropical air masses lead to the formation of fog that rapidly burns off after sunrise (see Figure 8-4). When Northeast Monsoon flow is very strong, fog from the Indian Ocean is occasionally advected over the northern coast. Short-lived morning fog also forms in marshes and low-lying areas. Marsabit, subject to upslope effects, has the highest frequency of fog. Suspended dust and haze is found over the banks of Lake Turkana. Smoke from forest or brush fires is present in the interior. In both instances, the effects on inflight visibility are more pronounced than on prevailing visibility.

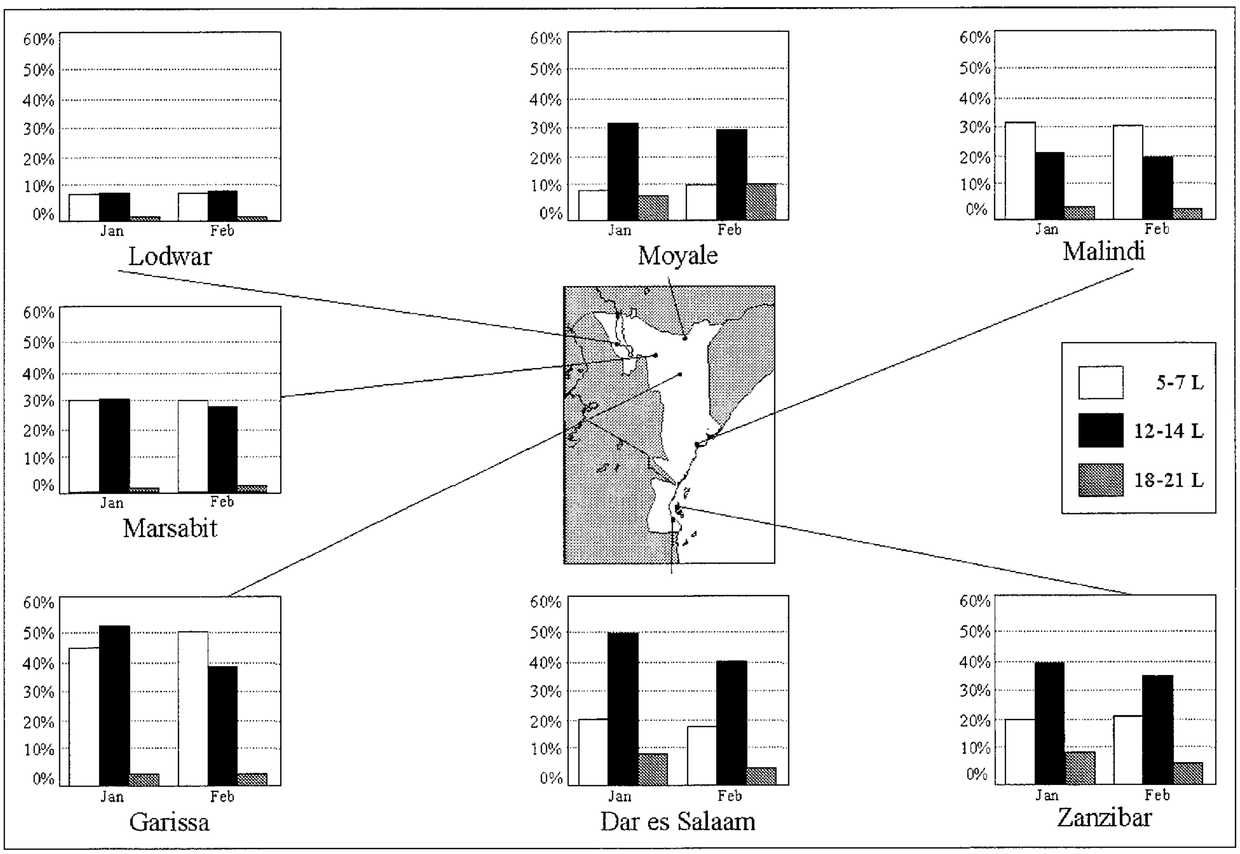


Figure 8-4. Secondary Dry Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. Northeast Monsoon flow comes from the Arabian Sea into the northern Indian Ocean, usually with speeds aloft from 10-20 knots. Speeds vary almost daily with the force of the monsoon, either in response to the deepening or weakening of thermal lows in southern Africa or to the presence of tropical cyclones near Madagascar. Over most of the region, wind speeds average 6 knots. Speeds rarely exceed 20 knots (see Figure 8-5), except for thunderstorm gusts to 50 or 60 knots.

Near the coast, winds veer slightly and weaken. Land/sea breezes modify both speed and direction of monsoonal flow. The primarily northeasterly winds are generally light at night and early in the morning due to the opposing effects of the land breeze, which lasts until about 0800L. During the day, when the prevailing monsoonal flow is strong, the sea breeze deflects it; when the prevailing flow is weak, the sea breeze overcomes it entirely. In the Zanzibar Channel, for example, the morning Northeast Monsoon flow is funneled around the island and winds are from the north-northeast. Later in the day, flow deflected by the sea breeze becomes east-northeasterly by early afternoon.

In the interior, monsoonal flow becomes more easterly, with southerly components at some locations. The Turkana Channel Jet and orographic effects play a large part in directing and controlling wind speeds, which are generally light at night, but increasing by mid-morning. Channeling of easterly flow in the northern foothills can cause higher surface winds at some stations; at Moyale, for example, speeds exceed 25 knots about 20% of the time in the morning and about 25% of the time in the afternoon.

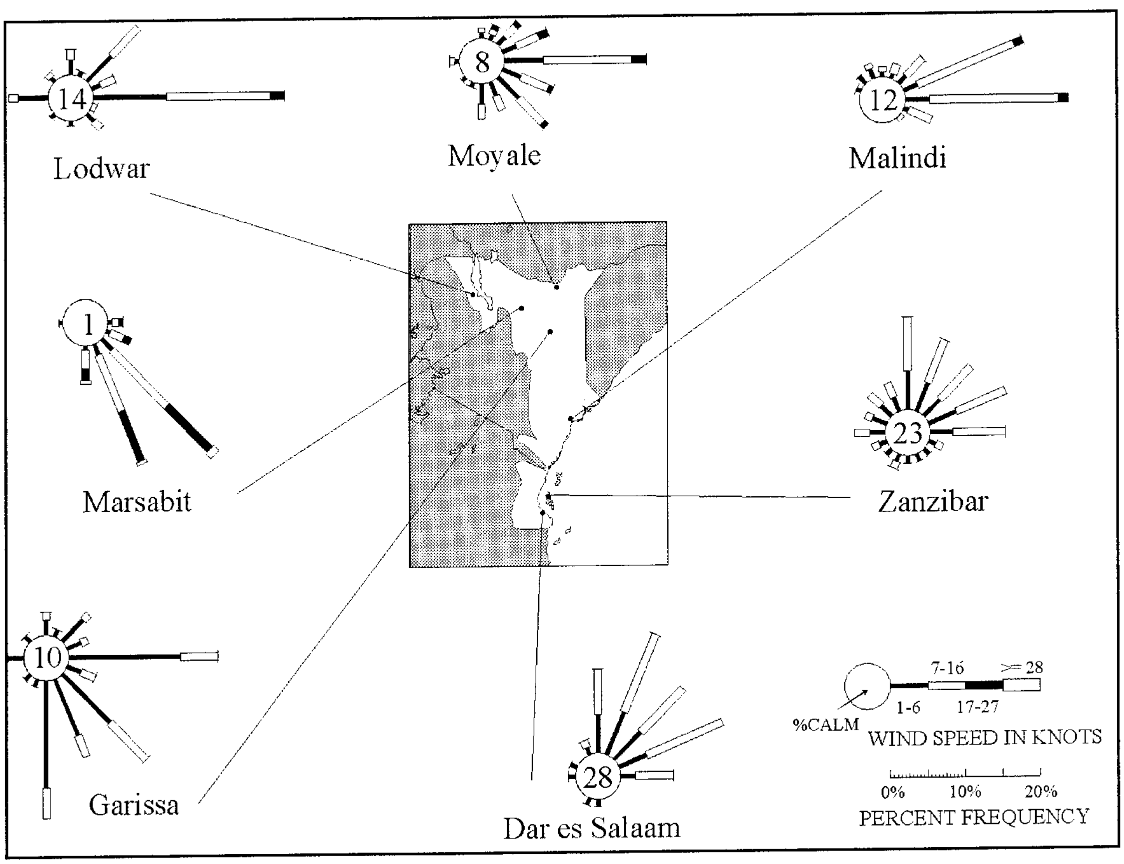


Figure 8-5. February Surface Wind Roses.

Precipitation is rare in the interior, but Marsabit, the highlands around Moyale, and the highlands on the northwest bank of Lake Turkana get higher rainfall amounts from orographic showers (see Figure 8-6). Along the coast, downpours can occur from midnight through the middle of the day from nocturnal showers that have developed over the Indian Ocean, usually when monsoonal flow is weak near the coast and when there is a steady nighttime land breeze. Convergence lines (which may be tropical waves from the Indian Ocean) sometimes produce showers, but amounts are usually light. Rainfall amounts increase southward as the coastline tapers and more moisture is available from the longer monsoonal fetch over the Indian Ocean.

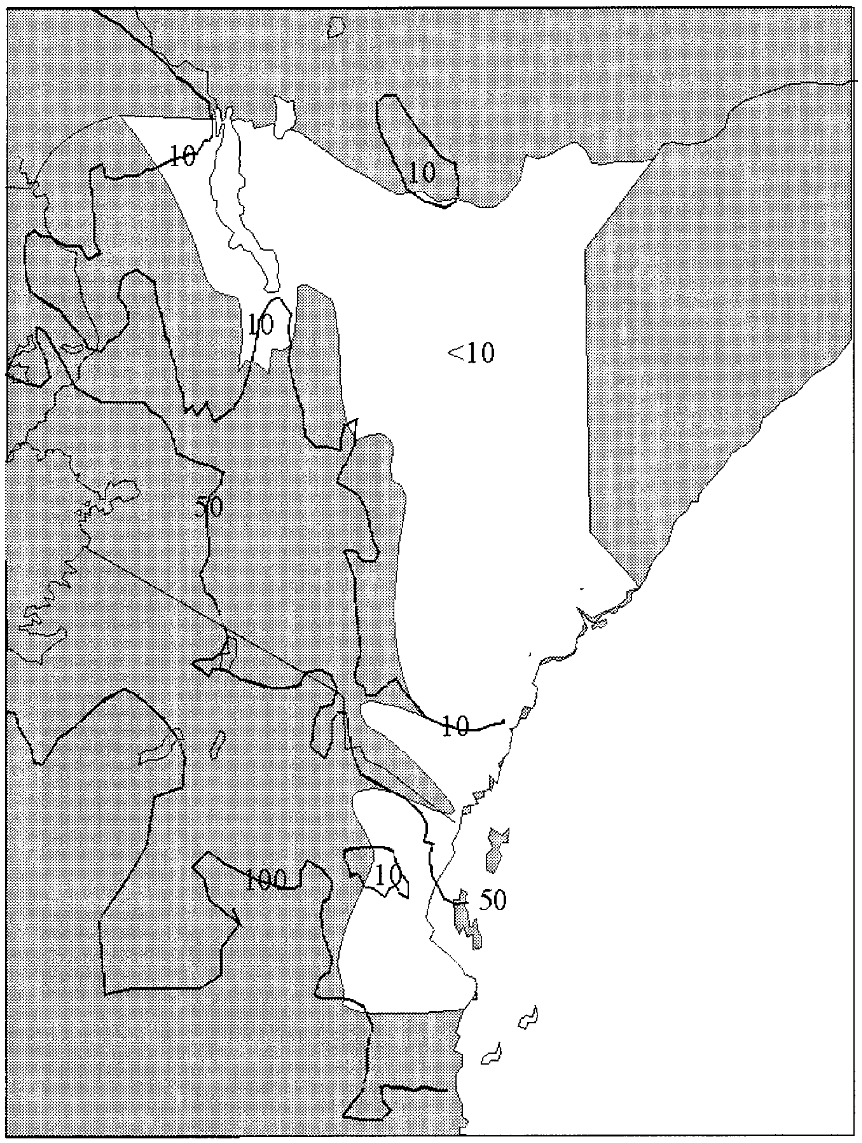


Figure 8-6. February Mean Precipitation (mm).

Thunderstorms are also rare during the dry season (see Figure 8-7) because of the stability that usually exists above the Northeast Monsoon flow. Within 55-95 km of the coast, thunderstorms can develop 2-3 times a month due to increased moisture and decreased stability. Bases are usually 2,000 to 5,000 feet, with tops to 50,000 feet.

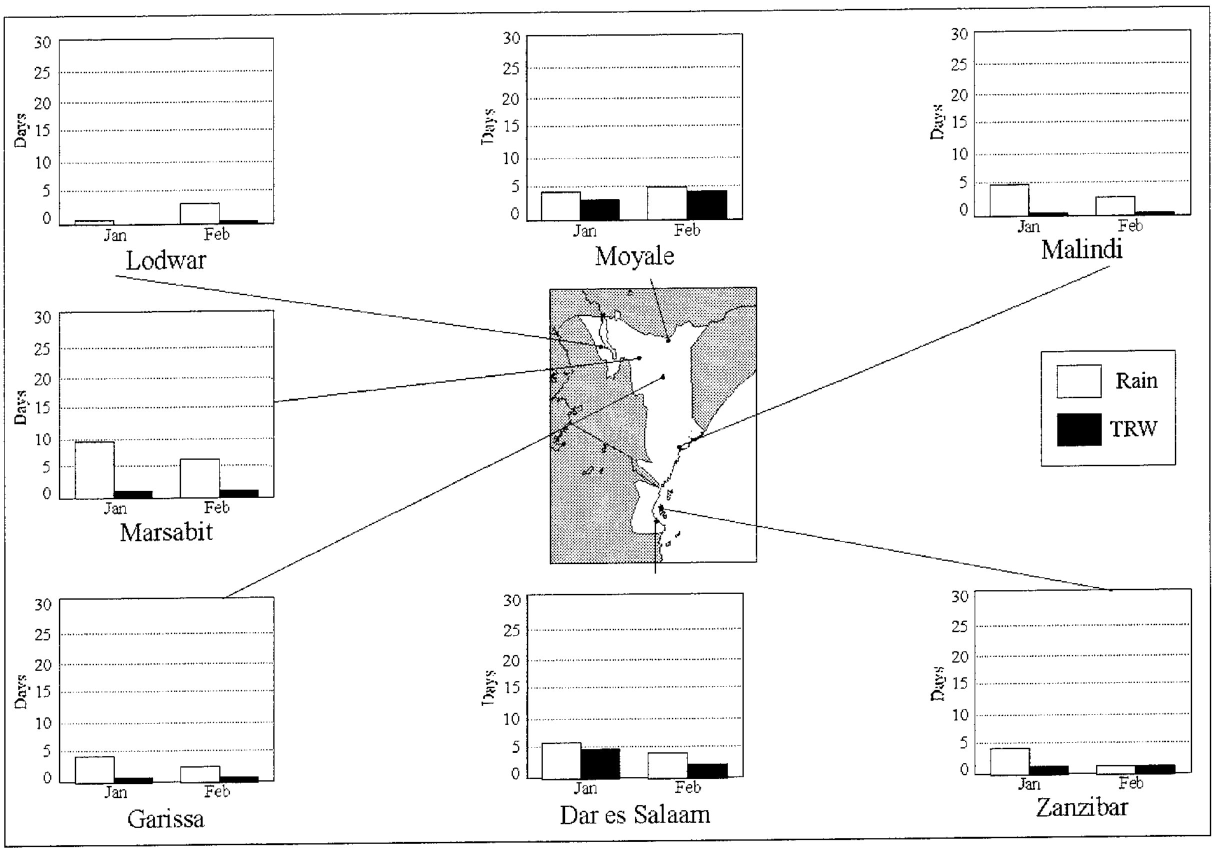


Figure 8-7. Secondary Dry Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. February is the hottest month throughout most of the region (see Figures 8-8a and b). The heat index is especially high along the coast due to the high relative humidities (usually greater than 75%). In the interior, temperatures can exceed 38° C, but they are lower near the southern shore of Lake Turkana. Record highs are from 33 to 35° C along the coast; record lows, from 18 to 21° C. Inland over the plains and lowlands, record highs range from 38 to 40° C; record lows, between 15 and 18° C. At higher elevations such as Marsabit and Moyale, record highs are 31 to 35° C and extreme lows 13 to 15° C. Wet-bulb globe temperatures range from 23° C inland to 26° C along the coast.

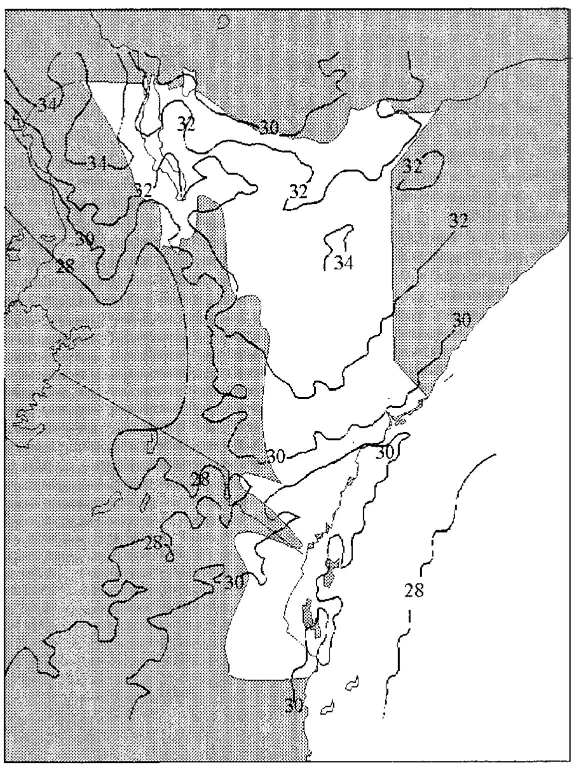


Figure 8-8a. February Mean Maximum Temperatures (° C).

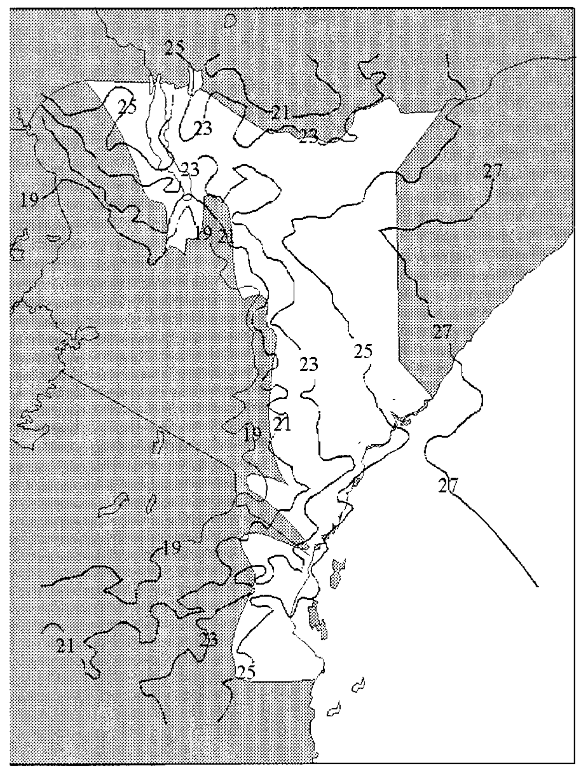


Figure 8-8b. February Mean Minimum Temperatures (° C).

General Weather. As the NET moves northward, this 3-month period marks the main (i.e., wettest and most severe) of the two wet seasons in Eastern Kenya. Winds are variable, with heavy rains (maximum between 0900 and 1200L) and wind squalls from the south or southwest. As the dry Northeast Monsoon weakens and is replaced by moister southerly flow from the Southeast Monsoon, convergence and instability are established. The resurgence of the Somali Jet off the coast controls low-level flow. More than half the annual rainfall occurs during this period.

The beginning of this wet season is usually marked by squalls and thunderstorms in the southern portion of the region. In the northern interior, violent, short-lived storms begin to occur by April. Marsabit Mountain receives more rain than the rest of the area, and is frequently covered in low clouds, particularly in the morning before 1000L. In the northern highlands near the Ethiopian/Kenyan border, orographic showers are produced by upslope flow, but rainfall amounts are still low.

Along the coast, showers and thunderstorms peak in April. On very rare occasions (twice in the last hundred years), tropical cyclones pass over the southern coast in April.

Sky Cover. The main wet season is very cloudy; convergence associated with NET movement produces widespread convective clouds (see Figure 8-9). Cumulus, stratocumulus, and cumulonimbus with bases at 2,000 to 3,000 feet usually form in the morning and increase through the day (see Figure 8-10). They occasionally last until a few hours before dawn. Cloud tops vary, but usually extend into the mid-levels. Stratus with bases from the surface to 1,000 feet usually forms underneath heavy showers or thunderstorms, occasionally obscuring hilltops.

On occasion, especially near the coast, overcast nimbostratus can form, with bases to 500 feet and tops to 8,000-10,000 feet. Bases are lower during heavy rains. Nimbostratus can last for 1-2 days. When the rain slackens, bases may lift to 3,000-5,000 feet, with patches of low stratus at 1,000 feet. If development becomes organized, there may be a continuous altostratus/nimbostratus cloud layer (with embedded cumulonimbus) lasting until a few hours before dawn. Cirrus is common.

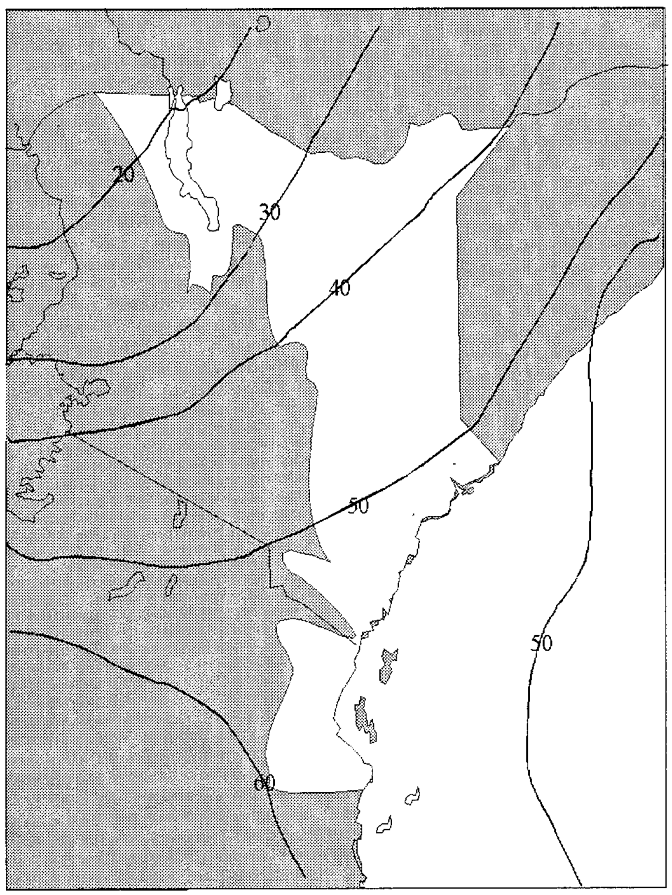


Figure 8-9. Main Wet Season Percent Frequencies of Ceilings.

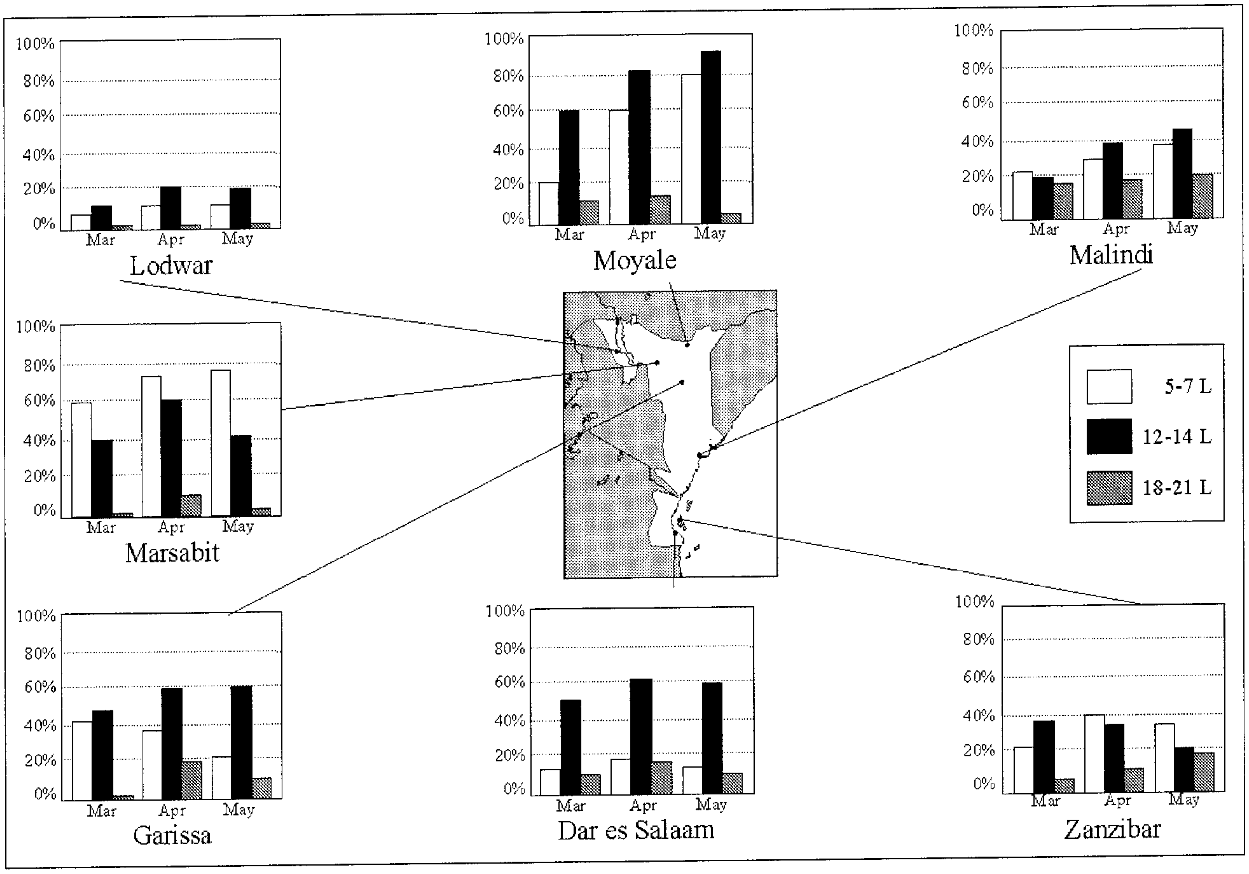


Figure 8-10. Main Wet Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility is restricted by precipitation and short-lived morning fog throughout most of the region (see Figure 8-11). Most fog forms after rain has fallen on the previous day, but it is usually light (visibilities are seldom below 4,800 meters) and it burns off rapidly. At Marsabit, upslope fog that can reduce visibility below 1,600 meters forms almost every morning.

Wind squalls or gust fronts from thunderstorms can produce sandstorms that reduce visibility to a few meters in the Lake Turkana area and in other parts of the interior. Visibility is occasionally reduced to less than 9,000 meters by suspended dust or smoke haze in the interior. Salt haze may affect the visibility along coastal areas in April and May as convection lessens.

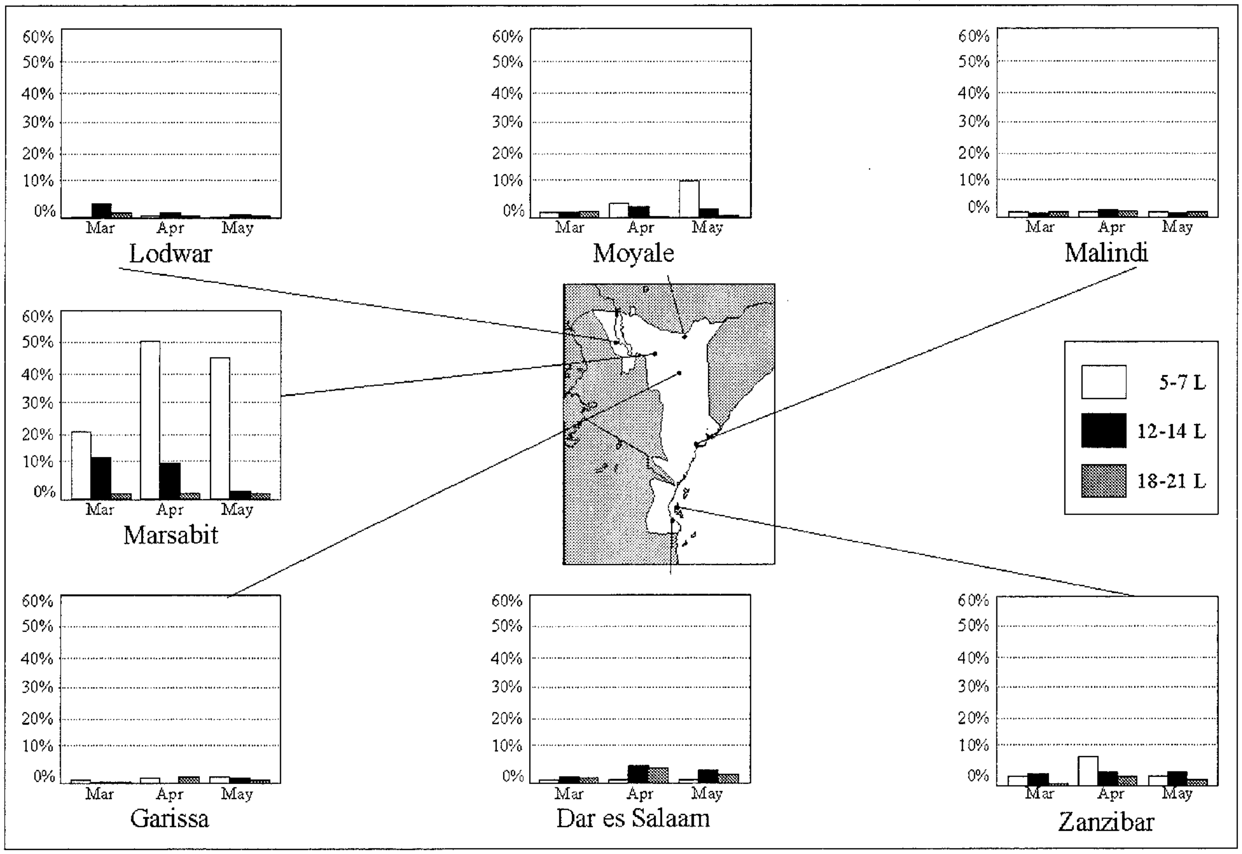


Figure 8-11. Main Wet Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. The southeasterly wind regime moves gradually northward as the wet season progresses. Prevailing wind flow changes gradually with the northward movement of the NET (see Figures 8-12a, b, and c). In the wet-to-dry season transition zone, where neither regime dominates, winds are often calm or light and variable. Along the coast, land/sea breezes continue to affect the speed and direction of the prevailing flow. At Dar es Salaam, winds are usually light and southeasterly (4-6 knots) in mid-morning, increasing to 8-12 knots in the afternoon as the sea breeze begins. Winds die down at sunset, becoming light from the southwest until morning.

Thunderstorms produce squalls, as well as gusts in excess of 60 knots, throughout the region. The highest frequency of strong winds is in the interior; the Turkana Channel Jet remains active here, as shown by the continuous southeasterly flow at Marsabit.

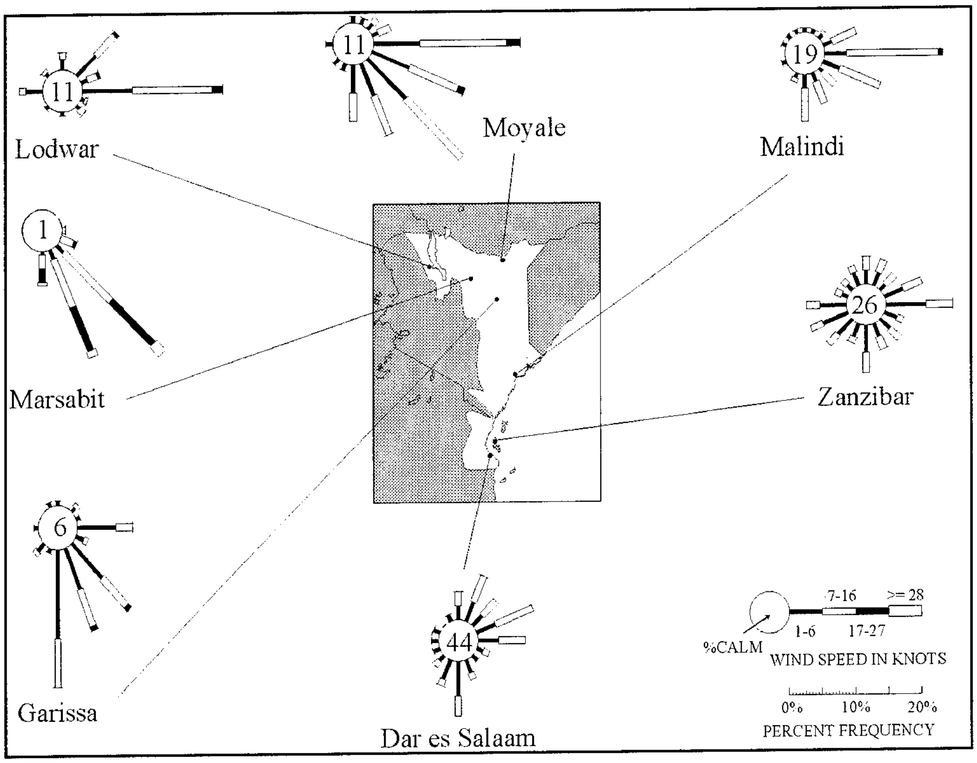


Figure 8-12a. March Surface Wind Roses.

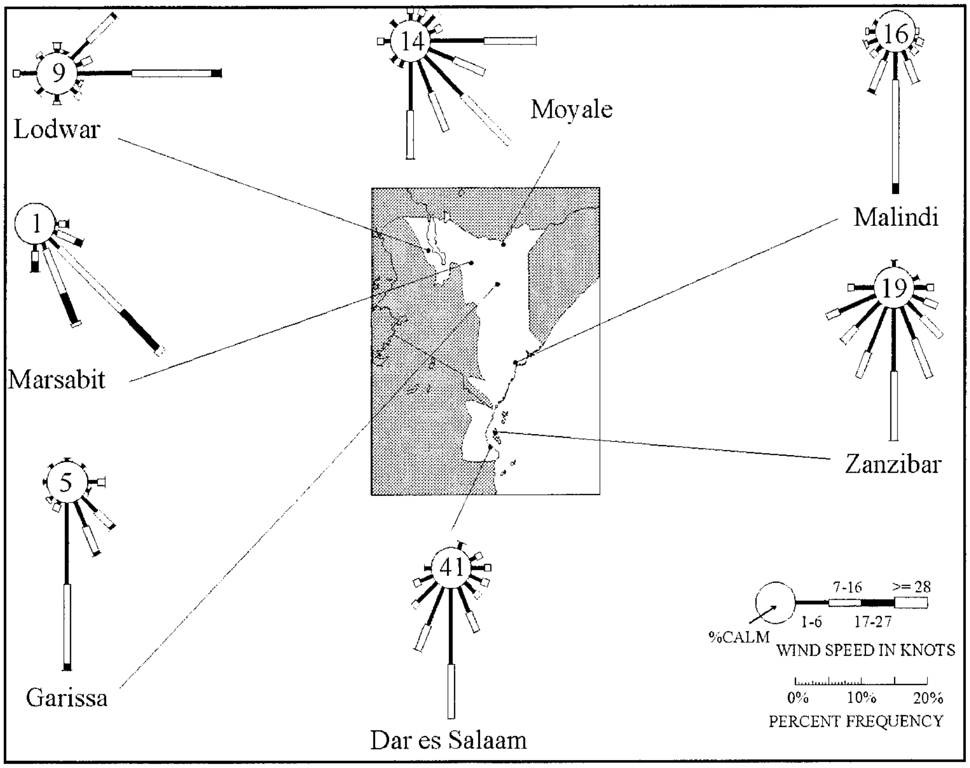


Figure 8-12b. April Surface Wind Roses.

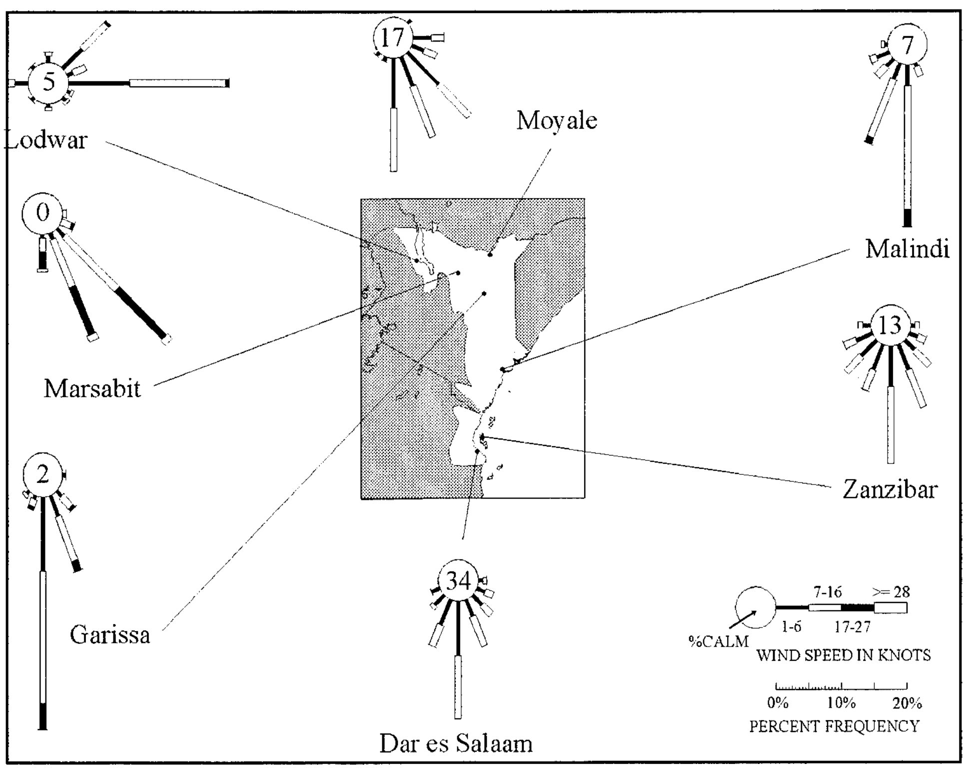


Figure 8-12c. May Surface Wind Roses.

Precipitation. Rainfall usually falls from widespread showers or thunderstorms, most of which develop in the afternoon. Nocturnal thunderstorms occasionally form along the southern coast in response to the convergence of the land breeze with the southeast monsoon. Continuous light or moderate rain occasionally falls near the coast, where it may persist for 24 hours or more. As shown in Figure 8-13, the highest amounts are along coastal areas and over the highlands near the Kenyan/Tanzanian border. More than 50% of the total annual rainfall occurs during this period, with the maximum in April (see Figure 8-14).

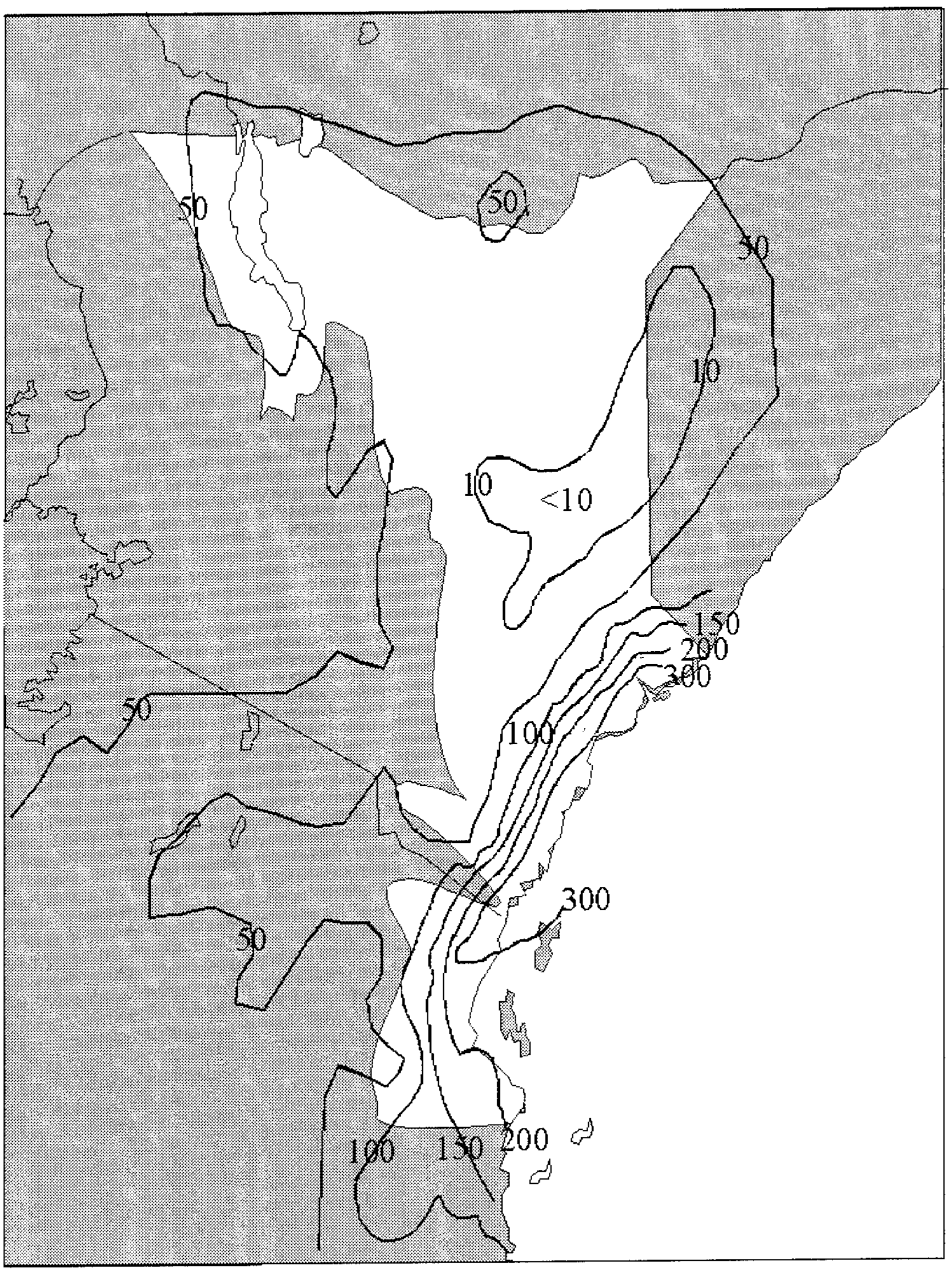


Figure 8-13. May Mean Precipitation (mm).

Thunderstorms can occur 24 hours a day. Over the interior, they are usually most active between 1500 and 2100L, with a minimum between 0600 and 1200L. However, they often form in the late morning over the south and west banks of Lake Turkana. Along the coast, thunderstorms either form over the landmass, or move in from the Indian Ocean, usually after 2100L. They are most active between 0100 and 0400L. Once triggered, thunderstorms are caught up in the easterly flow and move westward at 20-40 knots. Bases can be as low as 500 feet, while tops can exceed 50,000 feet.

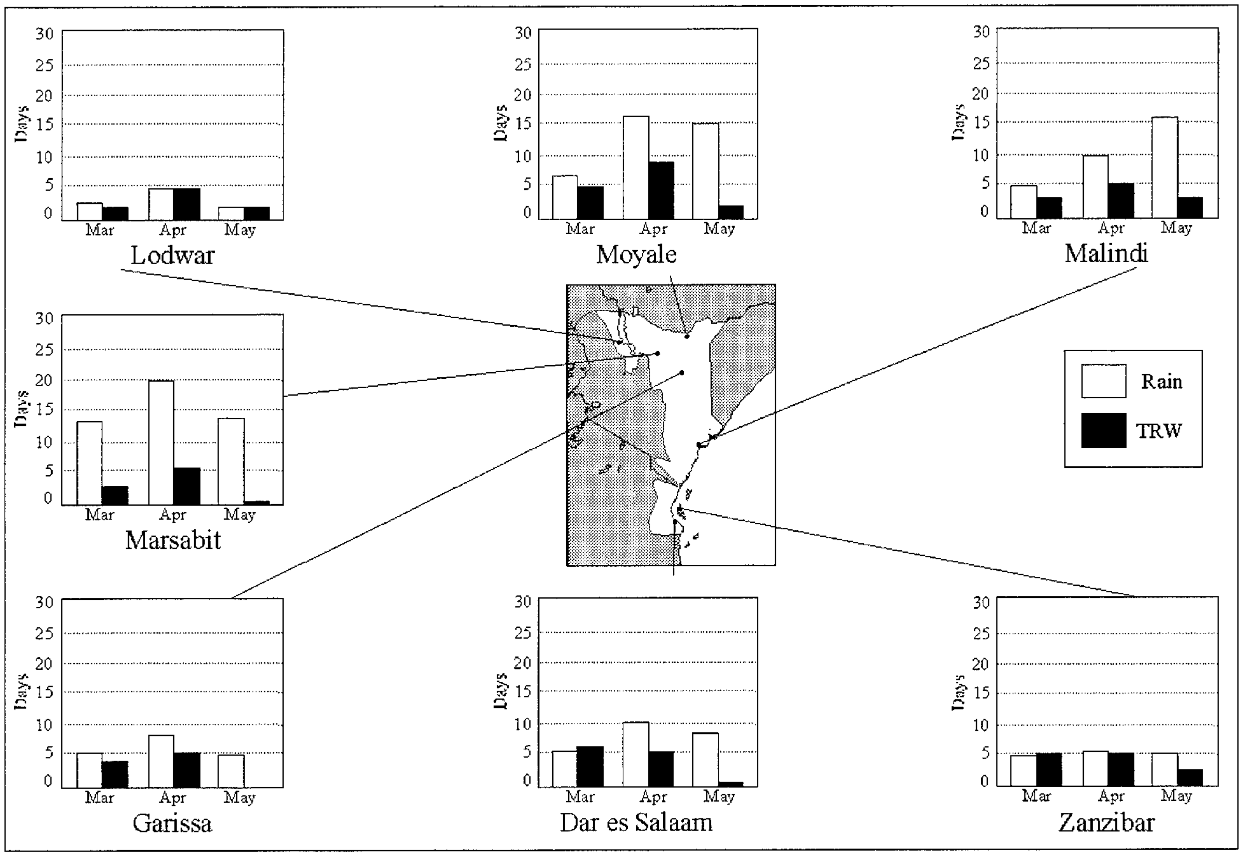


Figure 8-14. Main Wet Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. As shown in Figures 8-15a and b, mean temperatures drop slightly during the wet season. Record highs along the coast range from 36° C at Malindi in March and April to 33° C at Dar es Salaam in May. Record lows range from 16° C along the coastal plain in May to 21° C at Mombasa in March. In the interior, record highs range from 34°C in the lowlands during May to 41° C at Garissa in March. Record lows range from 13° C near Lake Turkana in April to 21° C in the Yatta Plateau, also in April. Marsabit has recorded highs of 30° C in March and April, with a record low of 13° C in May. Wet-bulb globe temperatures drop from 29° C along the coast to near 24° C around Lake Turkana.

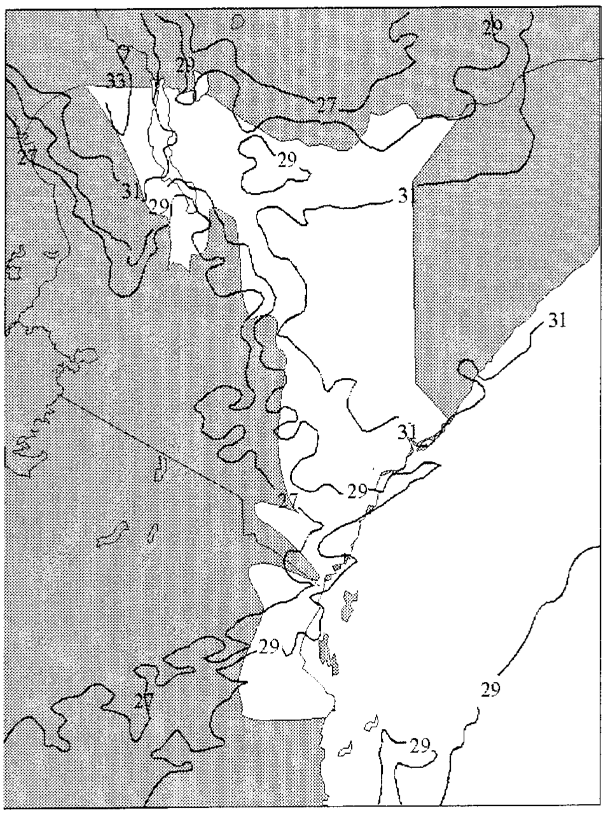


Figure 8-15a. April Mean Maximum Temperatures (° C).

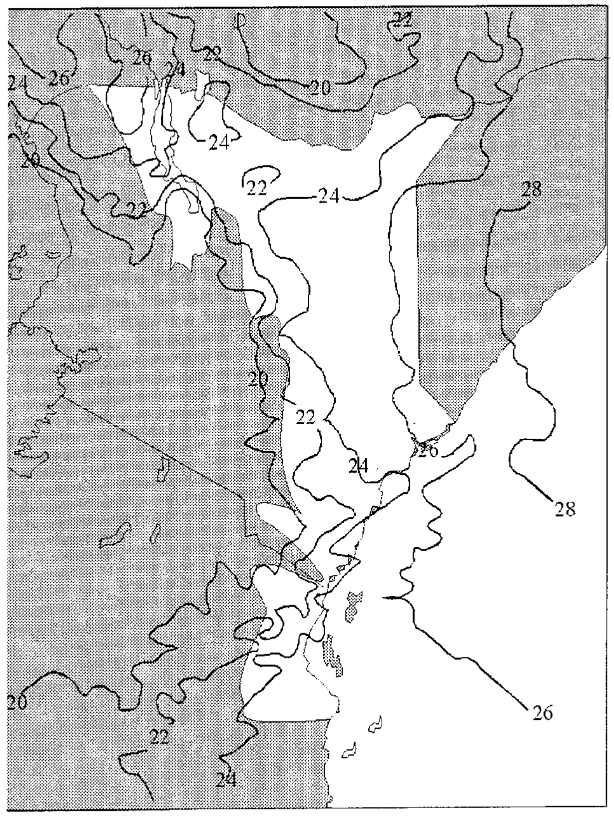


Figure 8-15b. April Mean Minimum Temperatures (°C).

General Weather. As the NET moves to the north of the region, the dry southeasterly monsoon flow becomes dominant, resulting in the driest season of the year. Conditions are relatively cool and dry, with occasional haze and/or stratus in the morning. Polar surges from the south sometimes form lines of showers over the Indian Ocean; they move onshore from the southeast. Relative humidities along the coast are very high in the morning, but moderate somewhat during the afternoon.

Maritime Tropical air is constantly advected into the region by the combination of the Southeast Monsoon, Somali Jet, easterly upper-air flow, and, to some extent, the Turkana Channel Jet. Although this flow can add moisture to the interior, capping by the Southeast Monsoon, as well as divergence at the surface, usually prohibits the development of showers or thunderstorms.

Sky Cover is at its peak (see Figures 8-16 and 8-17). Extensive stratocumulus, formed in the morning by diurnal heating, spreads out during the day. Bases are usually 2,000 to 3,000 feet; tops are only 2,000 feet higher. Altocumulus, with tops to 15,000 feet, forms occasionally. Nights are normally clear, with occasional short-lived evening stratus along the coast. Near Marsabit and the northern highlands around Moyale, moist southerly upslope flow produces low cloudiness that rises as stratocumulus in the afternoon.

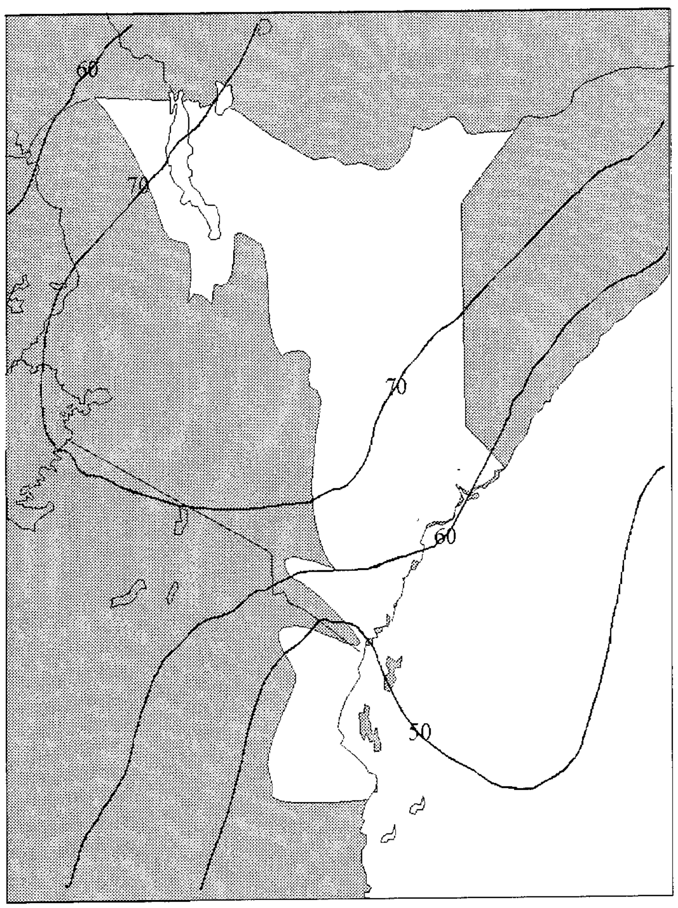


Figure 8-16. August Percent Frequencies of Ceilings.

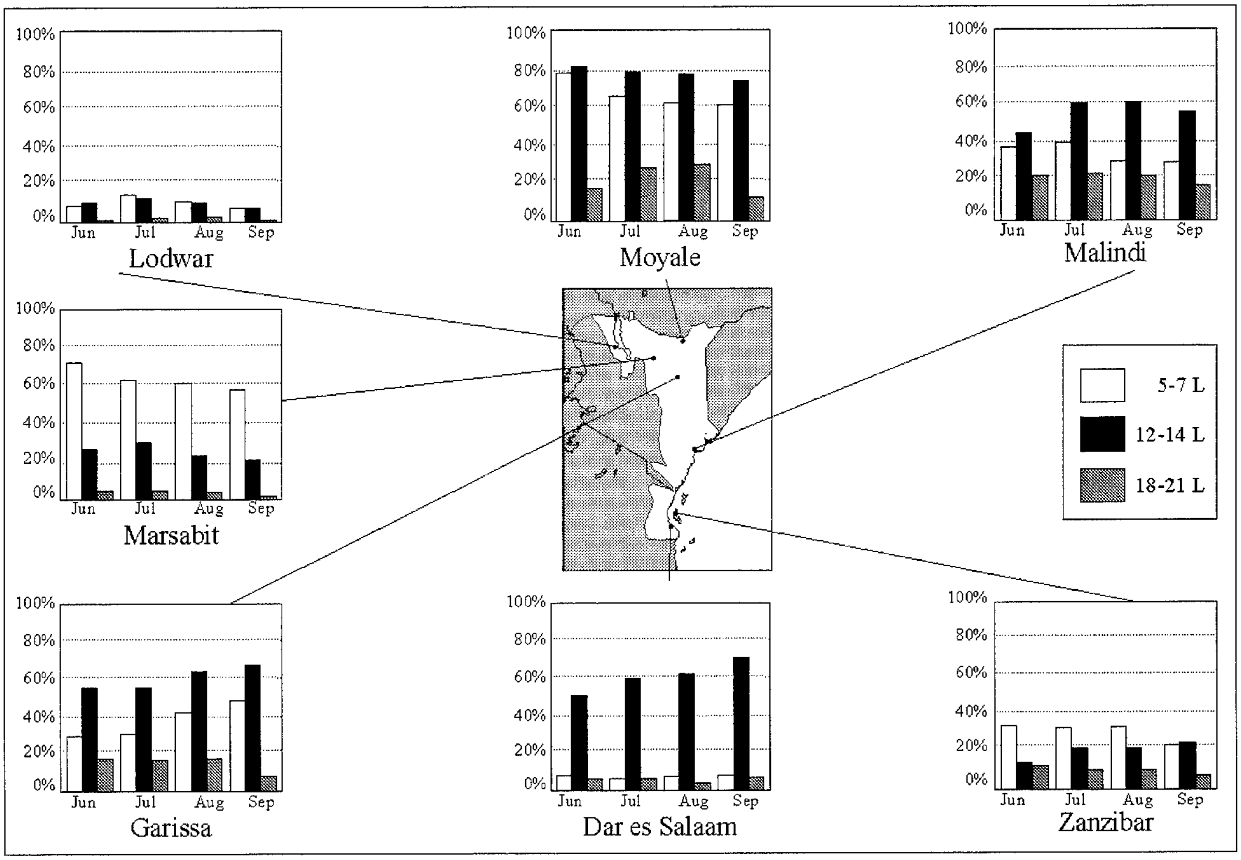


Figure 8-17. Main Dry Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility during the main dry season (southeast monsoon) is usually good (see Figure 8-18), except in the higher elevations where upslope conditions produce morning fog. Smoke from brush fires sometimes limits visibility in the interior. Morning sea haze can occur for a short time in the morning along the coast, but it rarely reduces visibility below 9,000 meters.

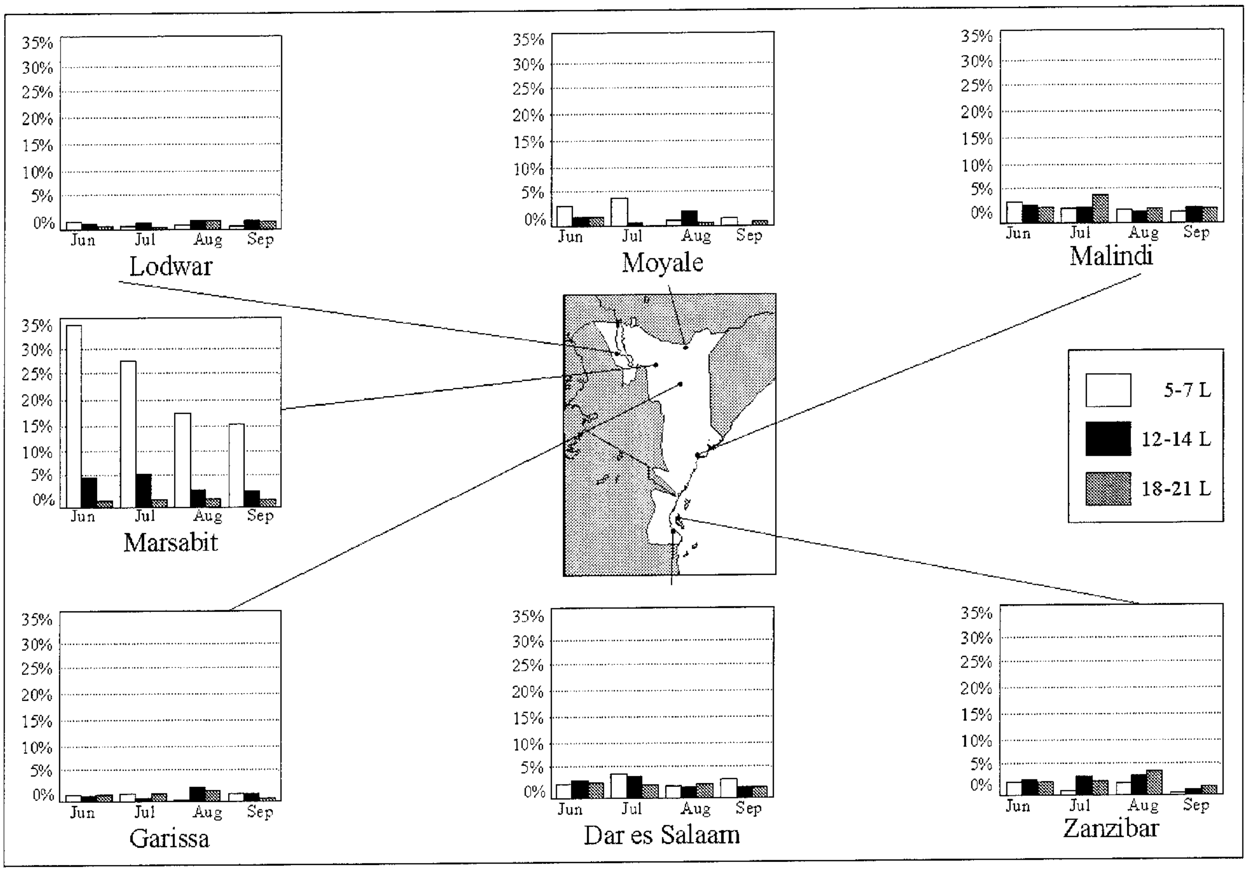


Figure 8-18. Main Dry Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. The Southeast Monsoon flow prevails along the coast and over the Indian Ocean as far north as the equator, spreading out fan-shaped as it moves onshore. Divergence once again occurs at the surface; southerly flow is split between the Saharan, Sudanese, and Saudi Arabian lows. Mean wind speeds are about 7 knots (see Figure 8-19.)

Along the coast, the sea breeze enhances southerly flow after 1000L; mean wind speeds reach 13 knots by 1500L. After sunset, the winds veer to light and southwesterly with onset of the land breeze.

In the interior, the winds are from the south or southeast, becoming easterly in the northwest corner of the region due to channeling between the highlands. Speeds are higher in some areas such as Moyale, where southerly flow is funneled. At Marsabit, speeds are above 25 knots in the morning about 20% of the time, due to the diurnal variation of the Turkana Channel Jet.

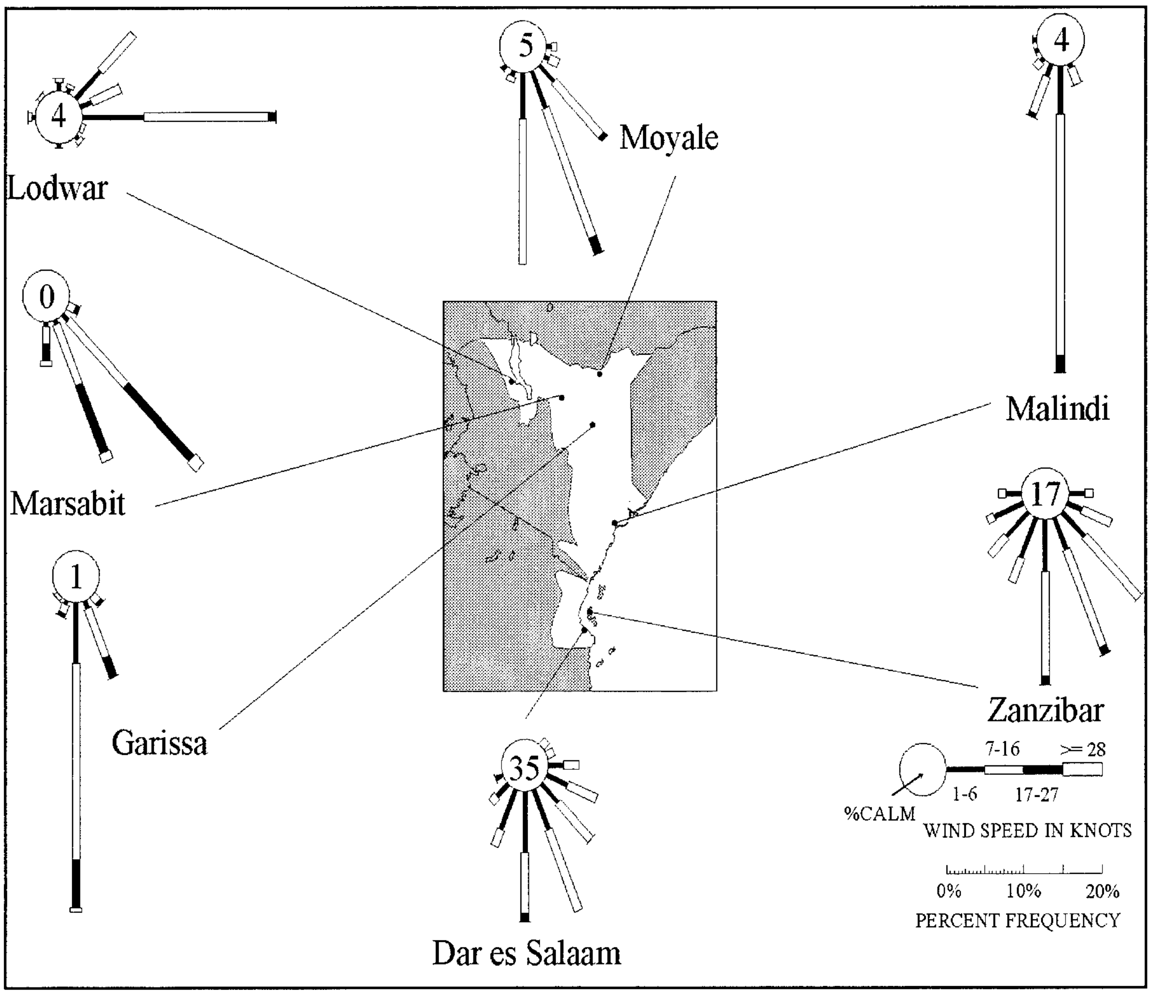


Figure 8-19. August Surface Wind Roses.

Precipitation is at its yearly minimum. Most of the region has less than 5 days a month with rainfall, which is mostly in the form of brief showers (see Figure 8-20). Malindi, on the northern coast, receives more due to the influence of the Somali Jet. Orographic lifting increases rainfall at Marsabit and in the area of Moyale. On occasion, primarily in June, heavy showers along the coast are produced by southern-hemisphere cold-air surges.

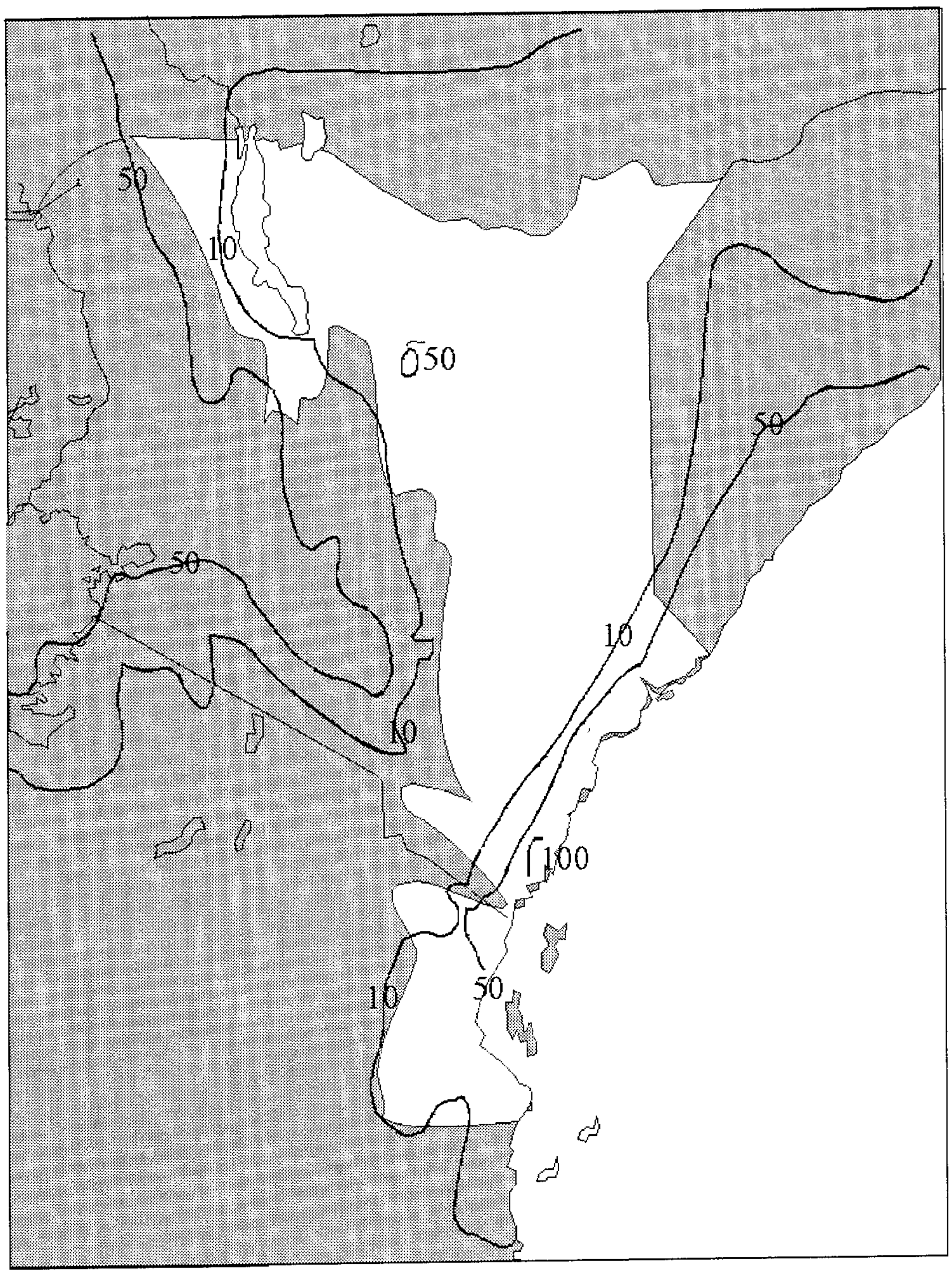


Figure 8-20. August Mean Precipitation (mm).

Thunderstorms are rare (see Figure 8-21), but they may occur in the northwest portion of the region over the south and west banks of Lake Turkana.

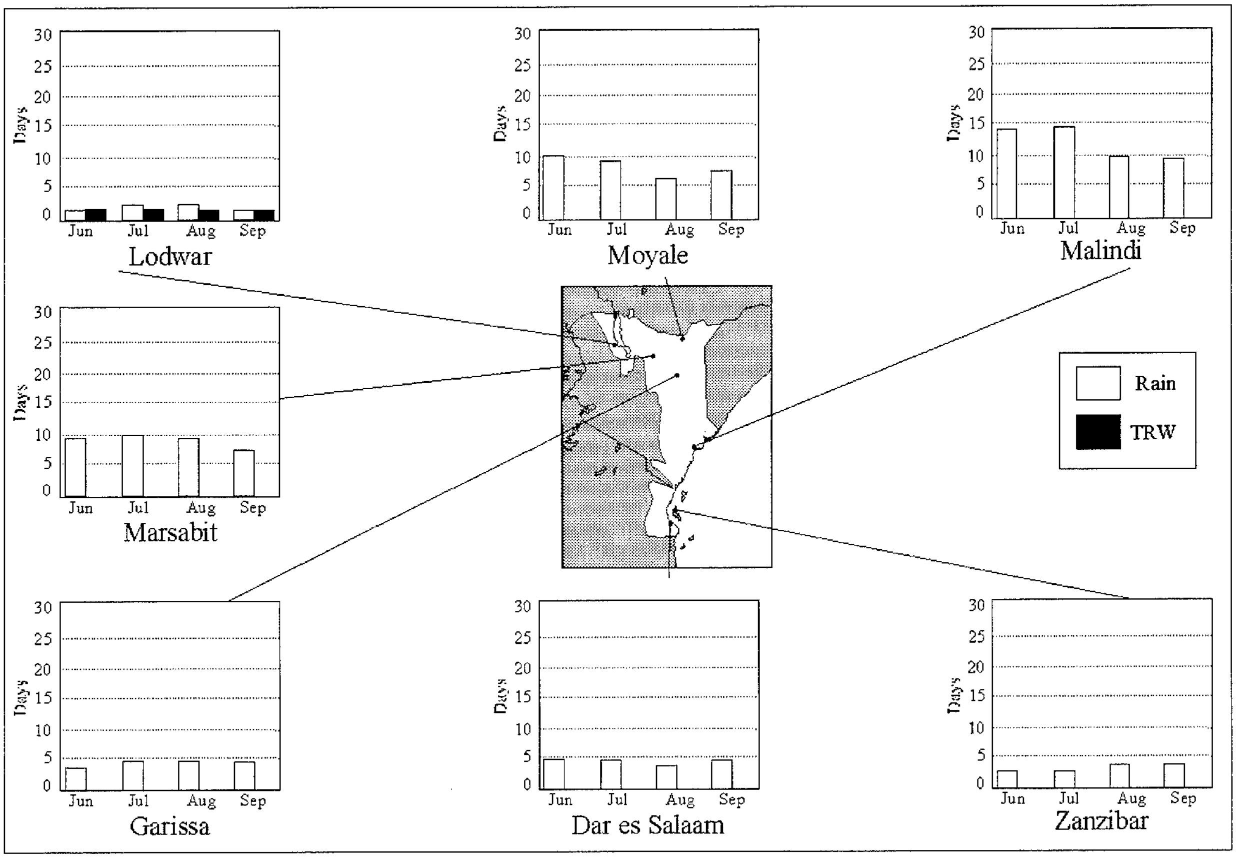


Figure 8-21. Main Dry Season Mean Monthly Rain and Thunderstorm Days.

Temperature. Since this is southern-hemisphere winter, these are the coolest months, but there is not much change from the rest of the year (see Figures 8-22a and b). Record highs range from 31° C along the coast near the Kenya/Tanzanian border in August and on the island of Zanzibar in July to 35° C along the northern coast in June and on Zanzibar in September. Record lows range from 11°C along the northern coast in June to 20° C on Zanzibar in June. Inland extremes are higher; they range from 38° C in August and September to 27° C on the Yatta Plateau in September. Record lows range from 12° C on the plateau in August to 21° C at Lodwar in June. Wet-bulb globe temperatures range from 23 to 25° C.

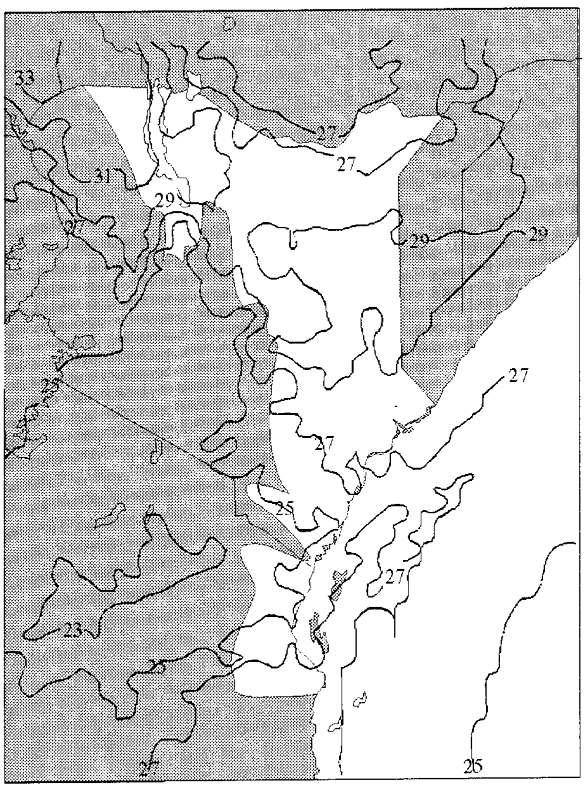


Figure 8-22a. August Mean Maximum Temperatures (° C).

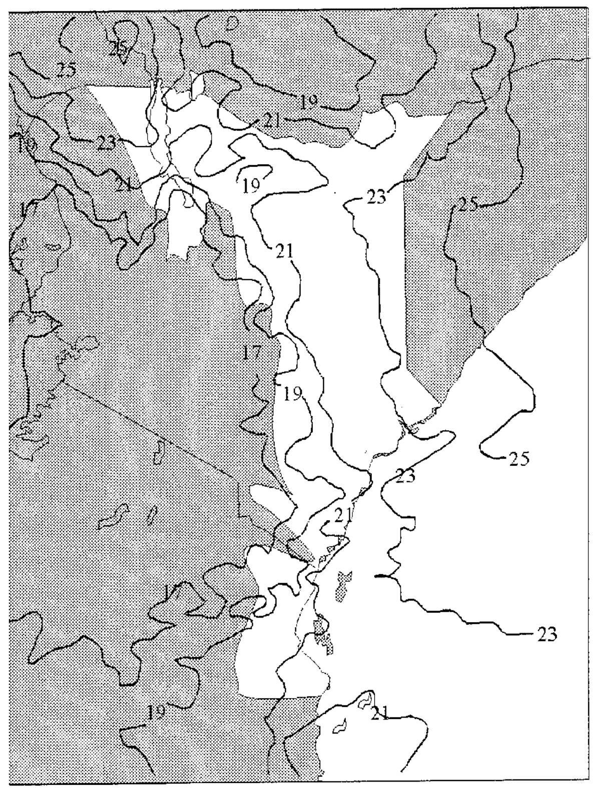


Figure 8-22b. August Mean Minimum Temperatures (° C).

General Weather. This season's weather is similar to that of the March-May main wet season, but drier and less severe. Wind shifts and rainfall begin in the north and move south. The encroaching surface flow is drier and more stable that the March-May wet season, with less rainfall. Thunderstorms are usually less severe.

As the Arabian High builds, pressures fall over southern Africa. As it moves back to the south, the NET displaces the wet Southeast Monsoon with drier Northeast Monsoon flow, which strengthens and moves underneath the moist southeast trade flow. This underrunning frontal effect produces duststorms in the northern portion of the region, as the "front" moves off the Ogaden Plateau in northern Kenya. By late December, the Northeast Monsoon begins to regain dominance throughout the region and the January-February dry season is about to be reestablished.

Sky Cover. Like the March-May wet season, this period is also very cloudy. Convergence associated with the NET produces widespread convective clouds (see Figure 8-23). Cumulus, stratocumulus, or cumulonimbus, all with bases at 2,000 to 3,000 feet, form in the morning and increase through the day; they can persist until a few hours before dawn (see Figure 8-24). Cloud tops vary, but they usually extend into the mid-levels and finally develop into cumulonimbus. Stratus, with bases from the surface to 1,000 feet, usually forms beneath heavy showers or thunderstorms; it occasionally obscures hilltops. On occasion, especially near the coast, overcast nimbostratus can form, with bases to 500 feet and tops at 8,000-10,000 feet. Bases are lower during heavy rains. The nimbostratus can last for 1-2 days. When the rain slackens, bases may lift to 3,000-5,000 feet, leaving patches of stratus at 1,000 feet If the development becomes organized, there may be a continuous altostratus/nimbostratus cloud layer (with embedded cumulonimbus) that lasts until a few hours before dawn. Cirrus is very common.

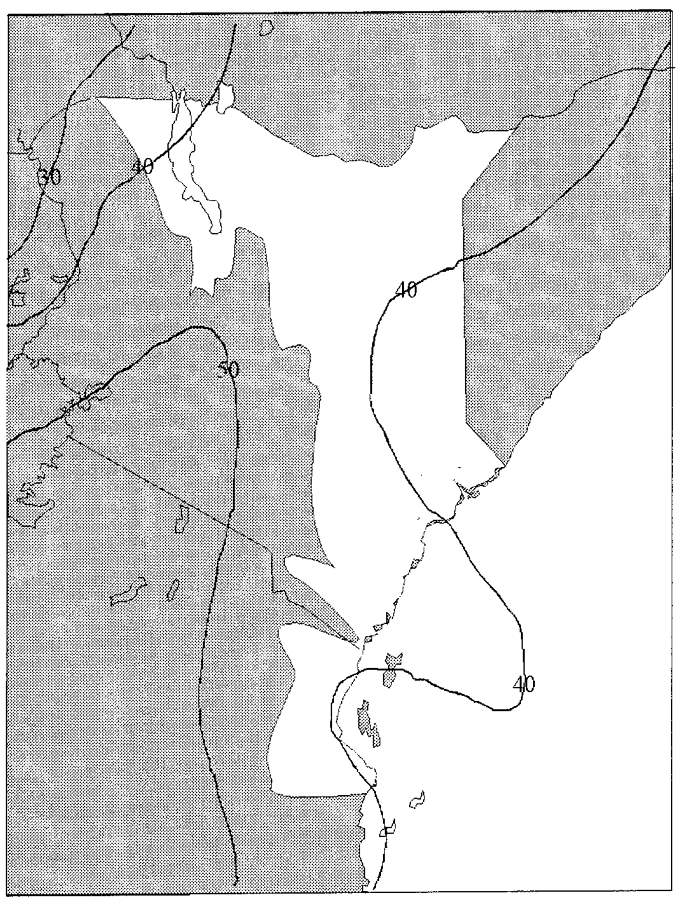


Figure 8-23. Secondary Wet Season Percent Frequencies of Ceilings.

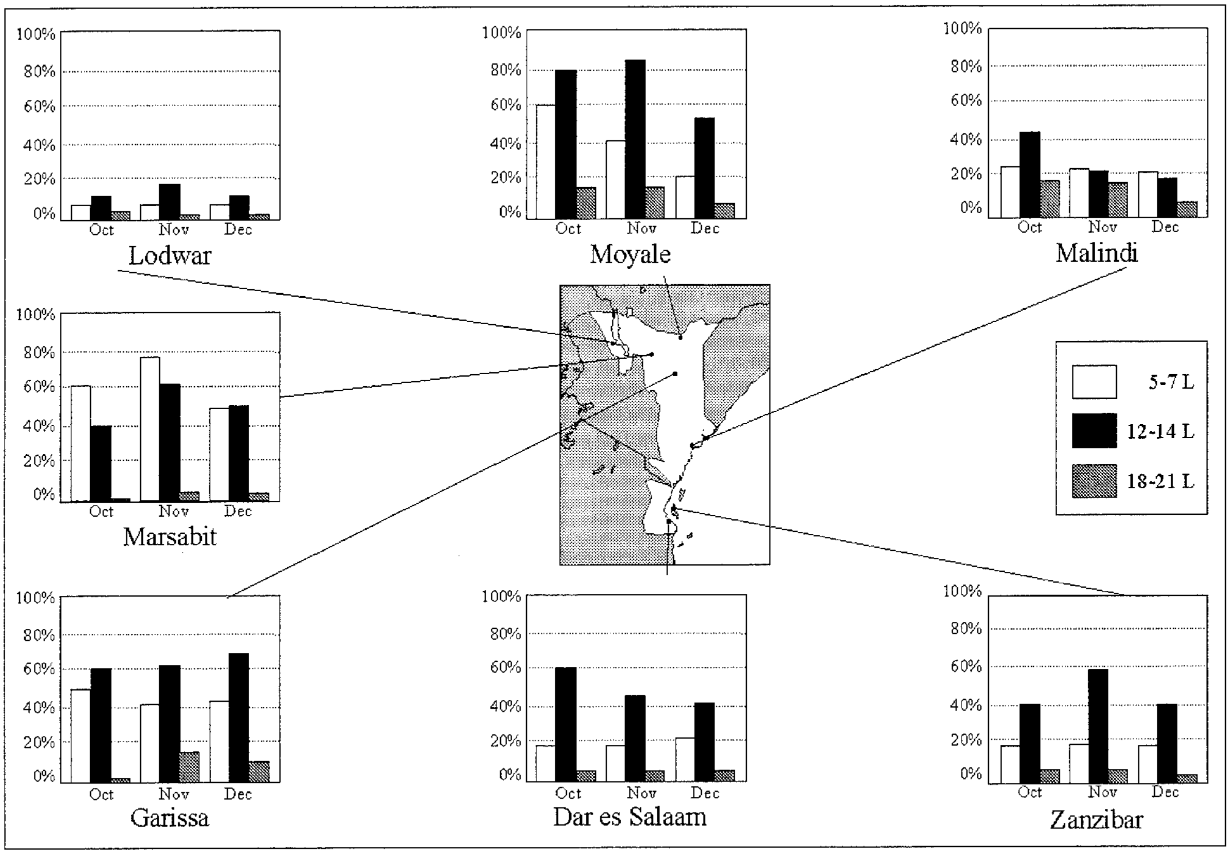


Figure 8-24. Secondary Wet Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility is restricted by precipitation and short-lived morning fog throughout most of the region. Most fog forms after rain has occurred on the previous day. It seldom restricts visibility to less than 4,800 meters and burns off rapidly. At Marsabit, upslope fog with visibilities below 1,600 meters forms almost every morning, especially in November (see Figure 8-25). Squalls or gust fronts from thunderstorms can produce sandstorms that reduce visibility to a few meters in the Lake Turkana area and other sections of the interior. Visibility is occasionally restricted to less than 9,000 meters by suspended dust or smoke haze in the interior.

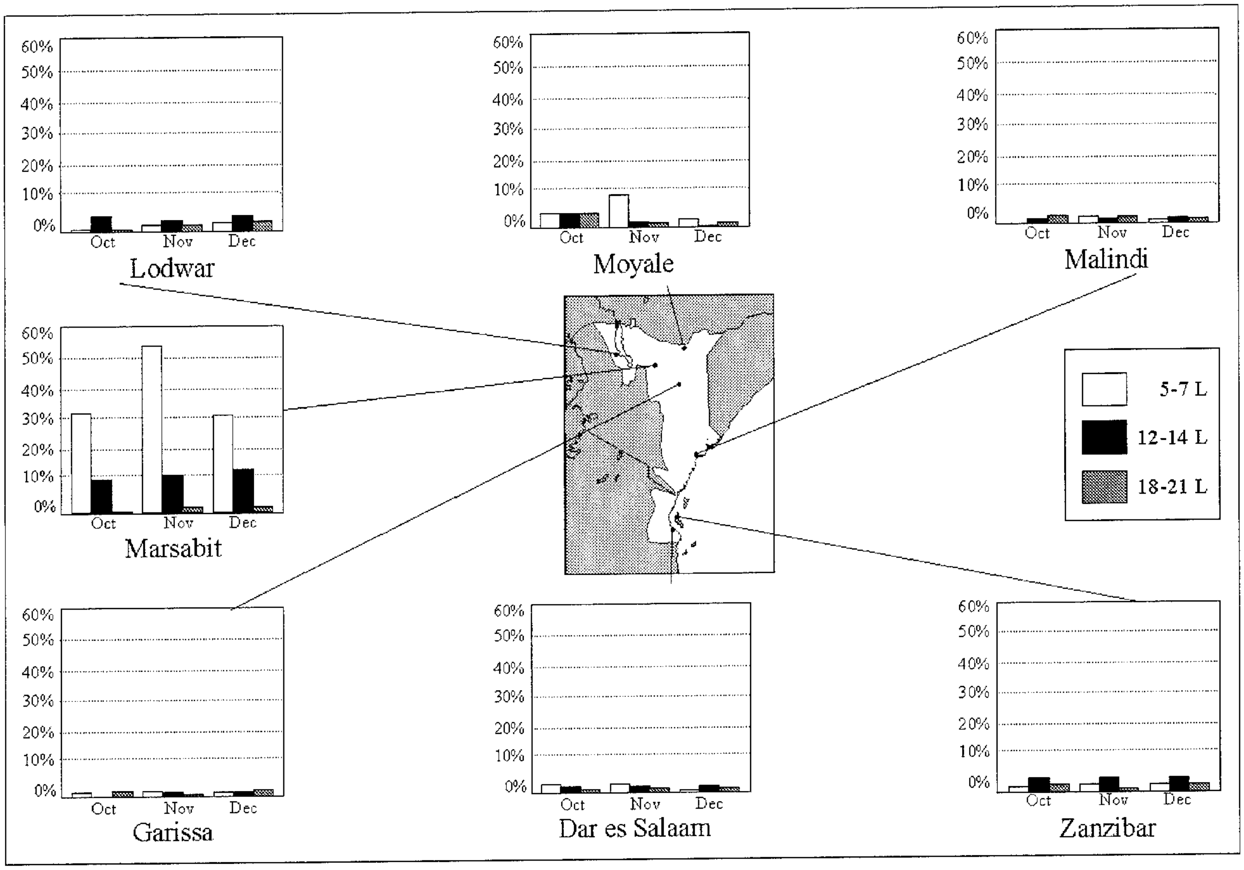


Figure 8-25. Secondary Wet Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds once again become light and variable as the NET moves southward. There are many periods of calm during October and November. Land/sea breezes dominate along the southern coast until December, when the Northeast Monsoon flow begins to regain dominance (see Figure 8-26). Speeds remain light (3-8 knots), except near heavier showers or thunderstorm. Thunderstorm gusts can exceed 50 knots.

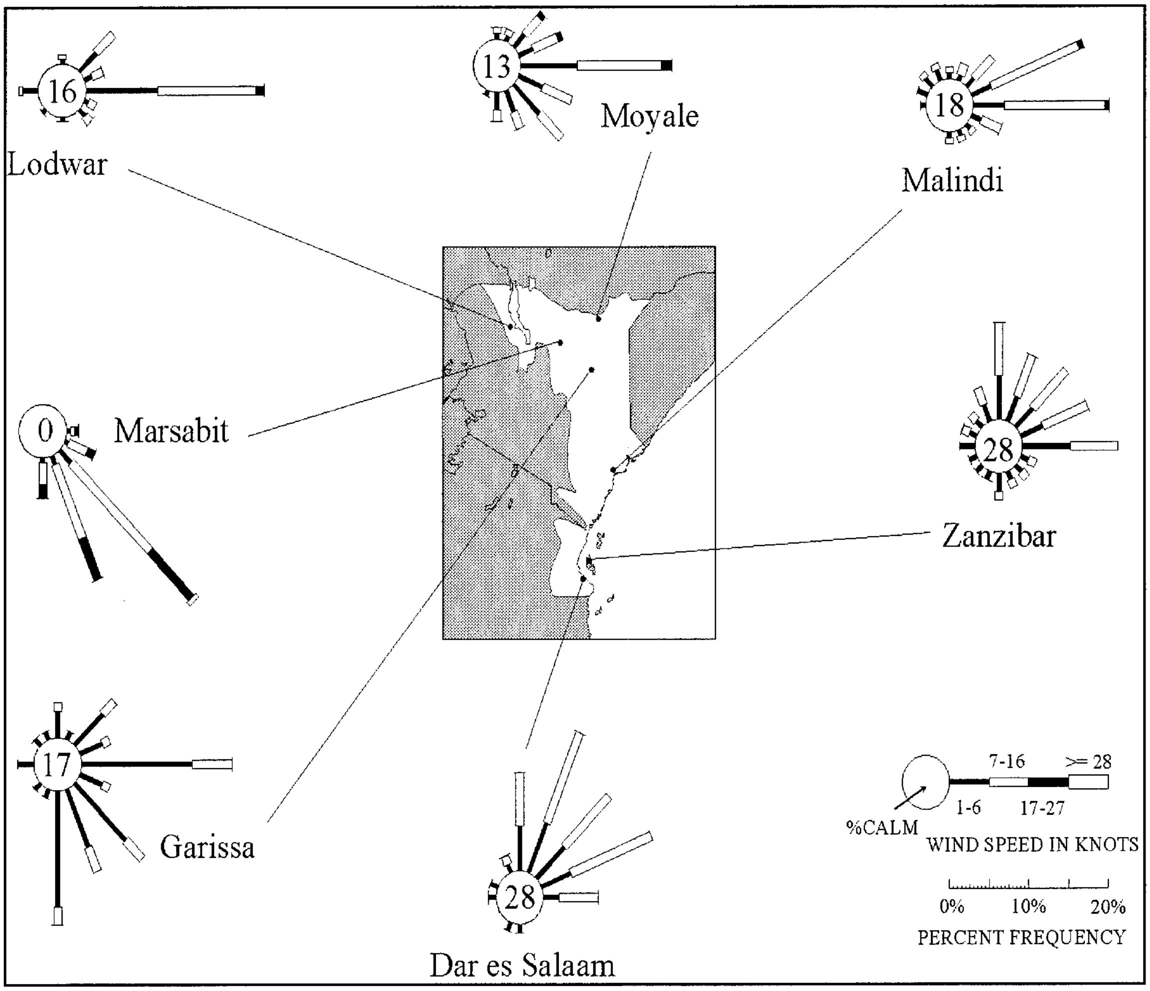


Figure 8-26. December Surface Wind Roses.

Precipitation. Rainfall is usually in the form of widespread showers or thunderstorms, that rarely last longer than an hour. Continuous light or moderate rain sometimes occurs near the coast, and may persist for 24 hours or more. As shown in Figure 8-27, the most rainfall occurs along the coastal areas and highlands near the Kenyan/Tanzanian border.

Most showers and thunderstorms develop in the afternoon. Nocturnal showers and thunderstorms can occur along the coast as convergence causes showers to develop over the ocean; these showers move onshore as easterly-type waves.

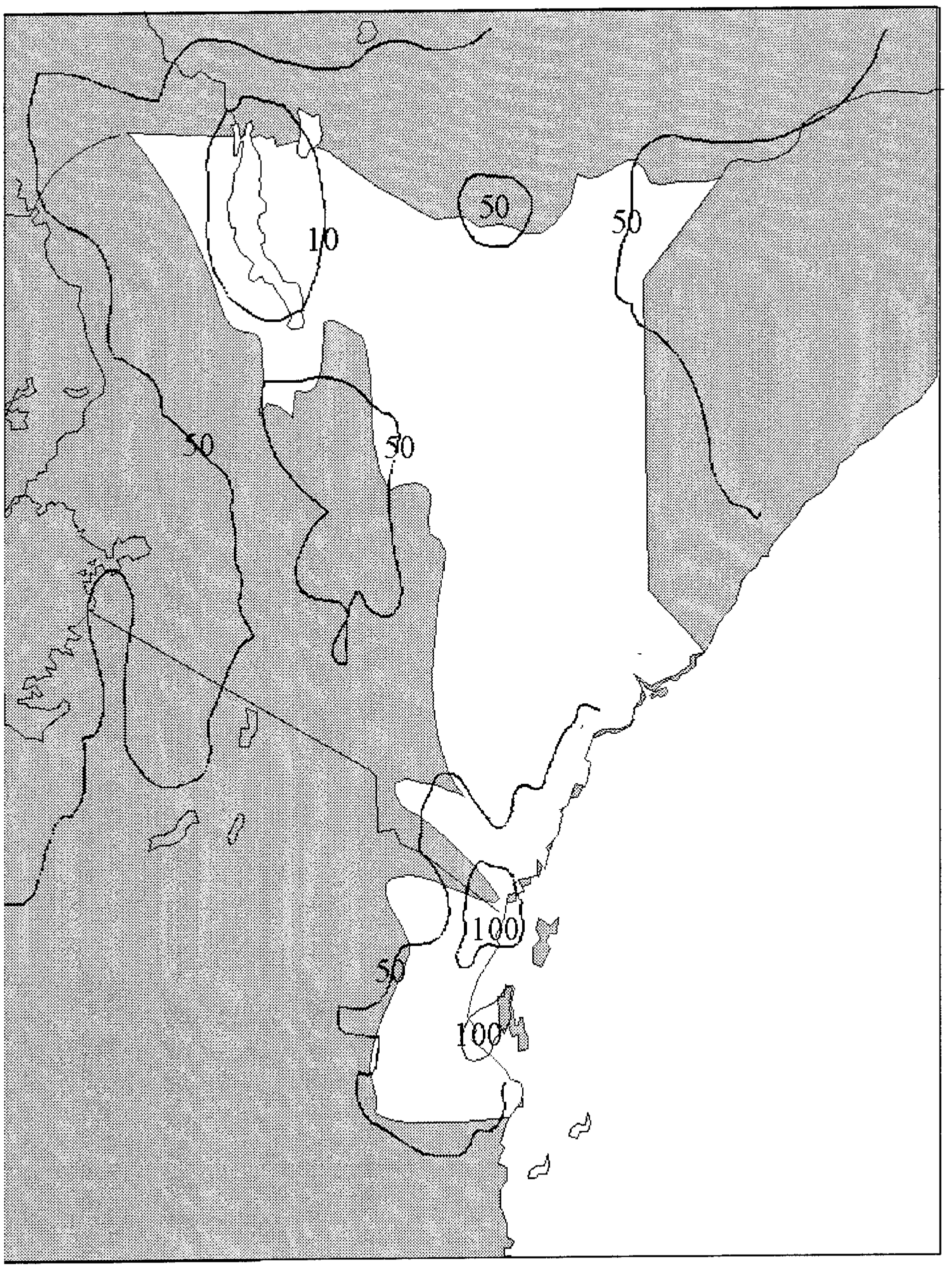


Figure 8-27. November Mean Precipitation (mm).

Thunderstorms can occur 24 hours a day. Over the interior, they are usually most active between 1500 and 2100L, with a minimum occurrence between 0600 and 1200L. Along the coast, most activity occurs between 0100 and 0400L. Thunderstorms may form over the landmass, or move in from the Indian Ocean after 2100L Once triggered, thunderstorms are caught up in the easterly flow aloft, and move westward at 20-40 knots. They are able to regenerate constantly due to the available moisture in the lower and mid-levels. Bases can drop as low as 500 feet (150 meters) while tops can exceed 50,000 feet (15,000 meters).

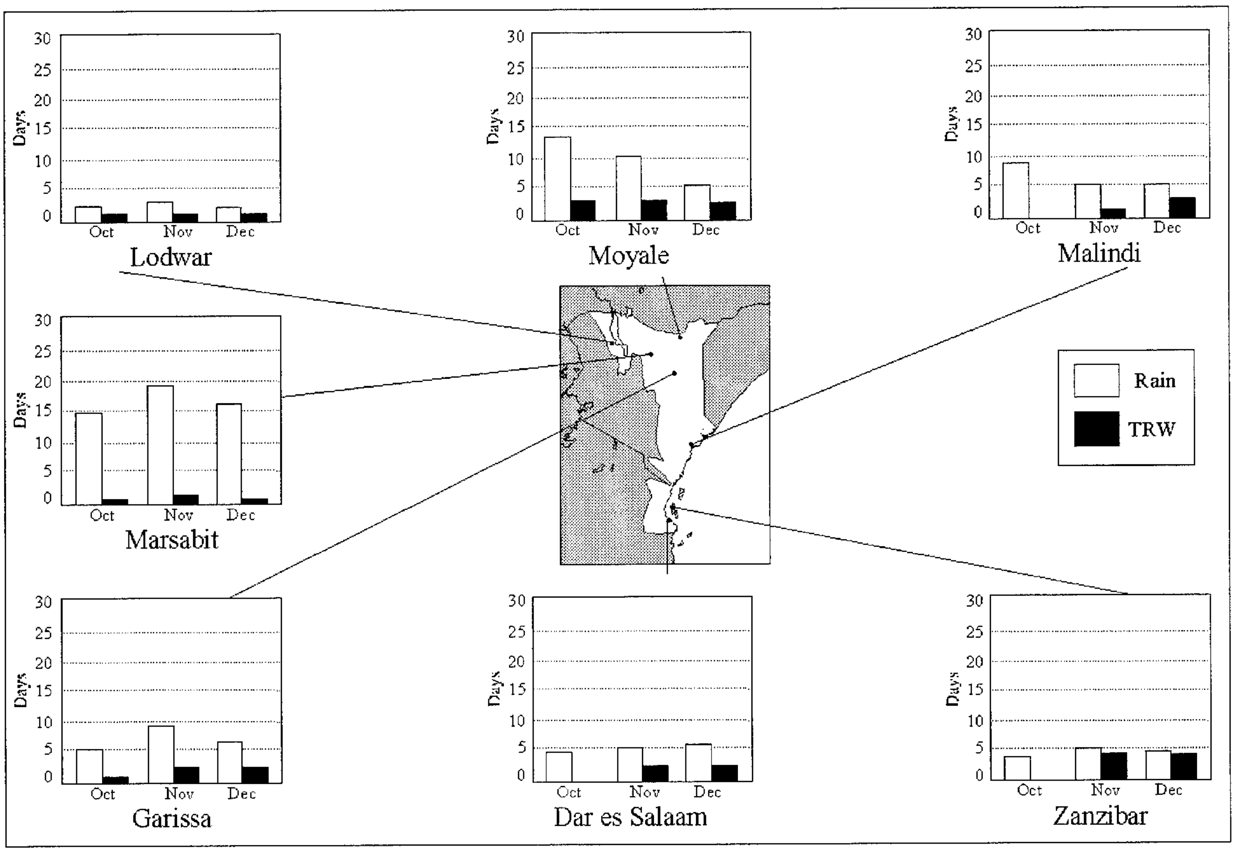


Figure 8-28. Secondary Wet Season Mean Monthly Rain and Thunderstorm Days.

Temperatures begin to increase as the sun moves southward (see Figures 8-29a and b). Record highs along the coast range from 33 to 36° C; extreme lows are between 16 and 21° C. Inland, record highs range from 35 to 39° C at Lodwar in October, while record lows are from 16 to 21° C below 1,000 feet. Wet-bulb globe temperatures decrease from 27° C along the coast to 23° C just southeast of Lake Turkana.

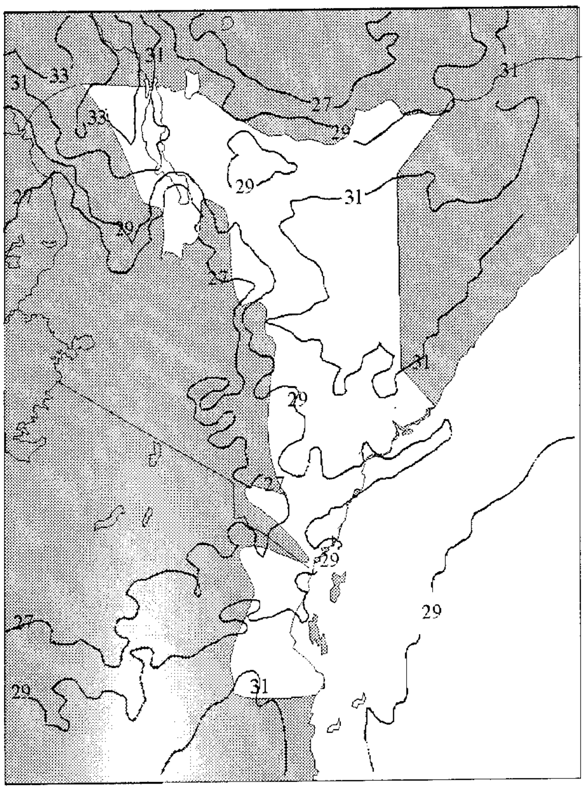


Figure 8-29a. November Mean Maximum Temperatures (° C).

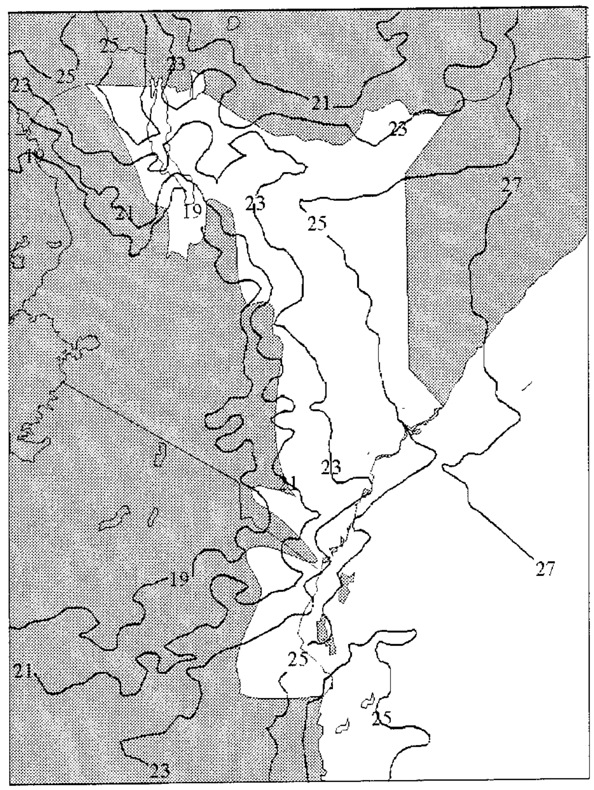
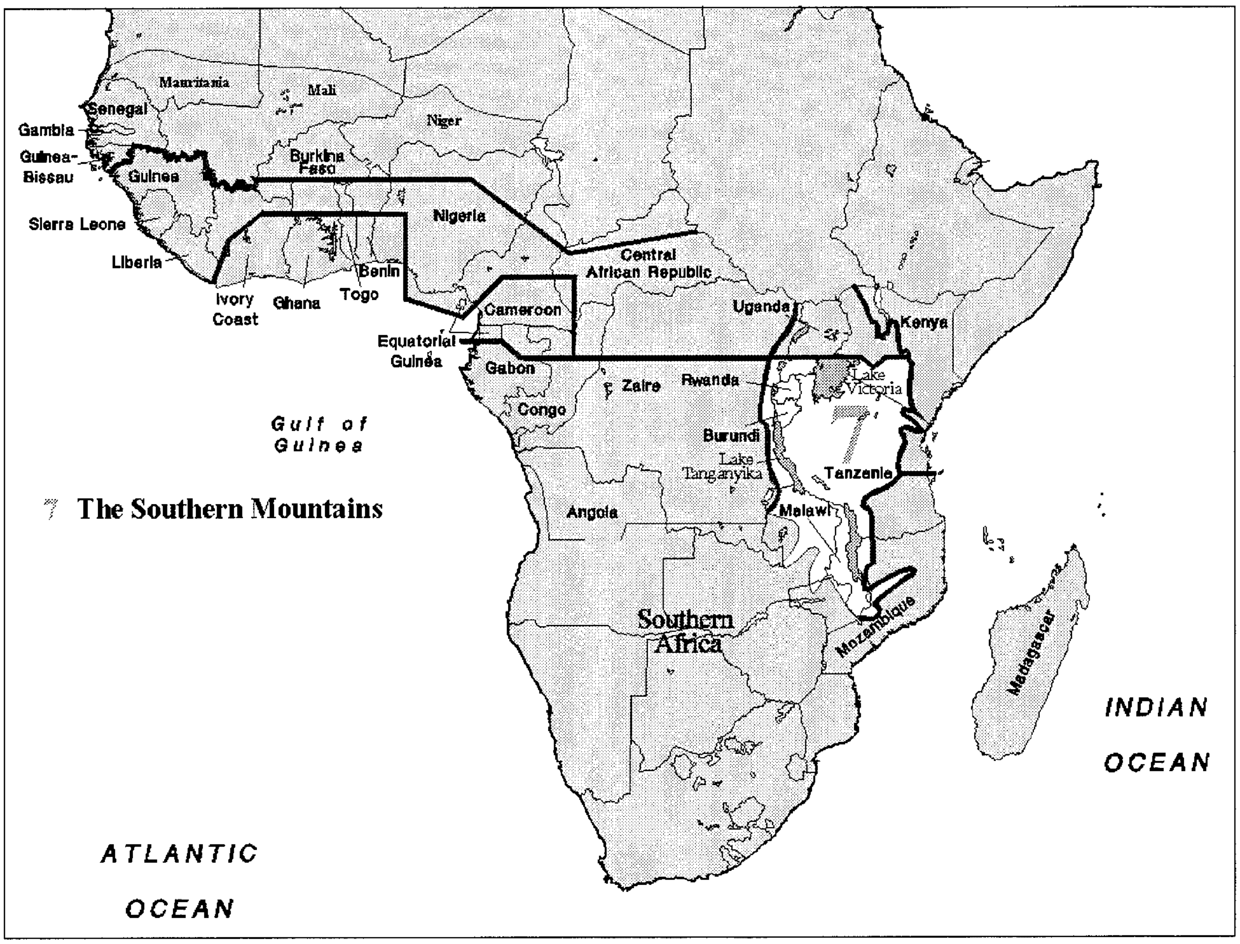


Figure 8-29b. November Mean Minimum Temperatures (° C).

Chapter 9

THE SOUTHERN MOUNTAINS

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) of the Southern Mountains, a zone of climatic commonality that includes southern Uganda, southwestern Kenya, most of Tanzania and Malawi, portions of Mozambique, western Zambia and Zaire, and all of Rwanda and Burundi.



SOUTHERN MOUNTAINS GEOGRAPHY

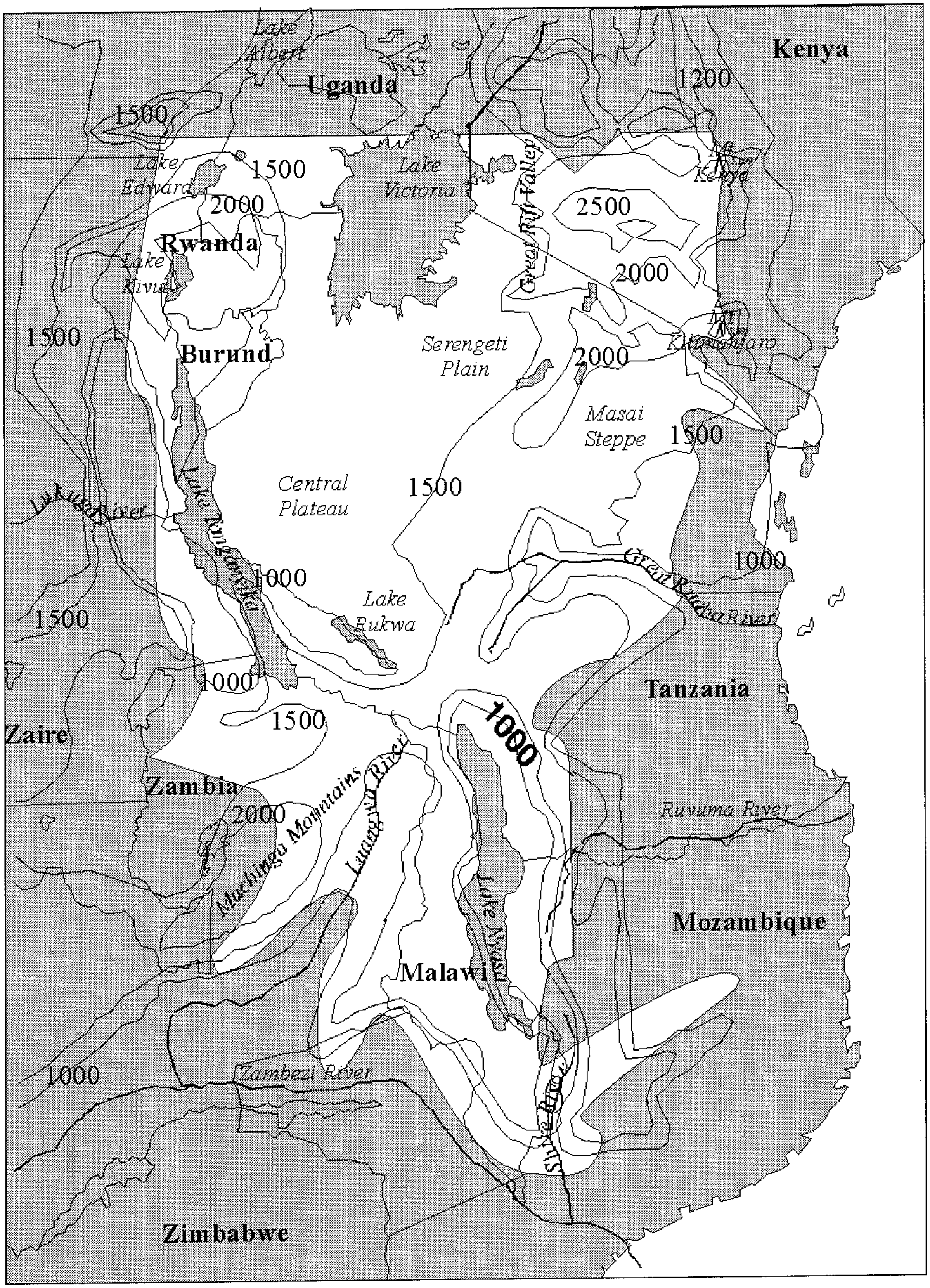


Figure 9-1. The Topography of Southern Mountains.

SOUTHERN MOUNTAINS GEOGRAPHY

Seasons. Under the influence of the Northeast Monsoon, there is a November-April wet season. The Southeast Monsoon results in a May-October dry season.

Boundaries: Boundaries are marked by the 1,000-meter contour everywhere except in the north, where reversal of the seasons at the equator defines the northernmost limits of the zone. The region extends southward from the equator to about 18° S.

Major Terrain Features. This zone is part of the Great African Rift System. Mountain ranges and plateaus along its east and west sides straddle rift valleys. The interior is marked by large basins, plains, and river valleys.

Lake Victoria and its basin lie on the equator in the north-central portion of the region. Terrain surrounding the lake is mostly flat, well-watered farm land, that quickly gives way to hills. To the east of the lake are the Kenyan Highlands, a complex mountain and plateau belt running west to east at between 1,500 and 3,000 meters; the highest point is Mount Kenya (5,199 meters). The highlands are bisected by a segment of the Great Rift Valley 65 km wide, bounded by escarpments 1,000 meters high. The valley floor is dotted with small lakes and inactive volcanos that contain steam vents and hot springs.

The highlands merge with the Eastern Rift System, an even more complex set of mountains and valleys that run roughly north-south. They include Mount Kilimanjaro, the highest point in Africa (5,895 meters) along the Kenyan/Tanzanian border. The mountain ranges parallel the coast 300-400 km inland, but are within 100 km of the coast near the Kenya/Tanzanian border. They extend southward toward Lake Nyasa, merging with the Western Rift System to form the Southern Highlands ofTanzania.

The Nyasa Rift System extends southward from the Southern Highlands around both sides of Lake Nyasa and its outlet, the Shire River. The western shoreline is higher and steeper than the eastern shoreline, but neither offers shelter along the lake. This system is composed mostly of rugged mountains and plateaus outlining the steep Zambezi River valley to the south; elevations range from 1,000 to 3,000 meters, gradually flattening out into the upper Luangwa River valley to the west. The Muchinga Mountains and escarpment border the lower Luangwa River on the west, with individual peaks reaching to more than 2,400 meters. The Muchingas reach northeast towards the Southern Highlands, leveling out onto a huge plateau to the northwest near Lake Tanganyika.

The Western Rift System extends west-northwest from the Southern Highlands. It is bisected by two segments of the Great Rift Valley that include the valleys of Lake Tanganyika, Lake Kivu, and Lake Edward. Terrain rises to the west of Lake Rukwa, forming a large plateau between it and Lake Tanganyika. Along the eastern shore of Lake Tanganyika, a series of small mountain ranges with abrupt slopes extend northward. Elevations rise to over 1,800 meters as the mountains near Burundi. The mountains are slightly higher along the western shore of Lake Tanganyika, and elevations also increase northward. Near Lake Kivu, elevations exceed 3,000 meters within a series of extinct and semi-active volcanos.

The high Serengeti Plain lies to the southeast of Lake Victoria; it is divided from the even higher Masai Steppe farther to the southeast by a small range of mountains.

The Central Plateau, with an average elevation of 1,200 meters, stretches west from the Serengeti Plain toward Lake Tanganyika and south to the Lake Rukwa depression. This is a sparsely populated area consisting of a dry plain with granite outcroppings, brackish swamps, and stream beds.

Rivers, Lakes, and Drainage Systems. The three largest lakes in the Great Rift System (Lake Victoria, Lake Tanganyika, and Lake Nyasa) are discussed on the next page. Lake Edward, Lake Kivu, and Lake Rukwa are also in the zone.

SOUTHERN MOUNTAINS GEOGRAPHY

Lake Victoria, which lies on the equator at 1,135 meters above sea level and covers an area of 83,000 square kilometers, is the largest lake in Africa, It lies in a huge valley between two mountain ranges that run roughly north-south. Lake Victoria is the source of the Nile River, which flows to the north.

Lake Tanganyika is the second largest lake in the zone and, at 660 kilometers, the longest fresh water lake in the world. Although fairly narrow (from 16 to 72 kilometers), it is 1,464 meters deep. Water temperature the year around is only 13° C. Lake Tanganyika is the center of an extensive drainage area, with several rivers emptying into it. The only outlet is the Lukula River, which flows westward from the lake into the Congo Basin. The shoreline rises steeply from the lake for most of its length.

Lake Nyasa, at 472 meters above sea level, is the third largest and southernmost of the major lakes. Its north-south length is 584 kilometers, while its width varies from 16 to 80 kilometers. It is enclosed by mountain ranges on the west, north, and east that rise rapidly from the shoreline. To the south, the lake is emptied by the Shire River, a tributary of the Zambezi. Famous for its supply of household tropical fish, Lake Nyasa maintains its temperature at 26-28° in the wet season, and 21 to 26° in the cooler dry season.

Rivers. Many rivers flow into or out of these lakes. In the east, several rivers drain into the Indian Ocean. The largest of these are the Ruvuma, which forms much of the border between Mozambique and Tanzania; and the Rufiji/Great Ruaha which flows from the Eastern Rift System and the Southern Highlands. Farther west, the Luangwa River flows from northern Zambia into the Zambezi River, which empties into the Mozambique Channel.

Vegetation. Most of the interior of the region is grass- or bush-covered plain, interspersed with "miombo" woodlands and thickets. The region is sparsely populated, and there is a high tsetse fly infestation. The mountains and highlands of the region are heavily forested on many of the windward slopes. Coffee and tea plantations are terraced into the slopes (along with other crops) in the higher elevations of Rwanda, Burundi, and Malawi. The Lake Victoria area is farmed extensively in cotton, coffee, banana, tea, tobacco, and cassava.

MAJOR CLIMATIC CONTROLS OF THE SOUTHERN MOUNTAINS

Near EquatorialTrough (NET). The NET moves rapidly south and west during November (the beginning of the wet season), producing what is known locally as the "short rains" in the northern and central portions of the zone. As the NET continues moving to its southernmost position of about 15° S (where it remains semistationary until March), a continuous rainy season prevails over the southern and western portions of the zone due to low-level convergence and instability. On its slower northward return, the passage of the NET produces the "long rains" of March and April in the northern and central portions. These rains can extend into May at some locations.

The Northeast Monsoon becomes dominant over most of the region from December through February as northeasterly low-level flow from the Arabian High is advected into the Kenyan Highlands and the Eastern Rift System. A weak subsidence inversion above the monsoonal flow becomes easterly and diverges once over the mountains; segments of the flow track toward several semipermanent low-pressure areas, including the one over Lake Victoria, the NET itself, the Great Rift Heat Trough, and the Zambian/Zaire Low. The northwestern portion of the region (southwestern Uganda, Rwanda, Burundi, and the adjoining part of Zaire) is under the influence of another branch of the Northeast Monsoon, the outflow of the Saharan High and Sudanese Low. This dry northwesterly flow from Egypt is moistened as it passes over the enormous Sudd swamp in southern Sudan. As the flow progresses farther southward it collects more moisture over Lake Albert and Lake Kivu, and is quickly lifted orographically into the mountains.

The Southeast Monsoon. The dry southerly-southeasterly flow from the South Indian Ocean High (and to a lesser extent, the South African High) moves over the region to produce a May-October dry season. With the NET far to the north, a strong subsidence inversion that averages 2,000-4,000 meters in depth caps the monsoonal flow, resulting in very stable conditions. Although orographic lifting occurs along the windward slopes of the mountains, the subsidence capping above the monsoon usually prevents convective development. Extensive stratiform cloudiness, however, is produced on the windward slopes.

Topographical Effects. The mountain ranges that encircle the region produce upslope cloudiness and precipitation on windward slopes, affect wind direction and speed, force foehn-type winds on leeside slopes, and cause rain shadows over portions of the zone. They also interact with the large lakes, which add moisture to the atmosphere, modify wind flows, and serve as source areas for thunderstorms. At several locations, the combined influences of the lakes and mountains create abundant rainfall, while only a few kilometers away harsh desert-like conditions exist. Specific seasonal topographic influences are described as "Major Climatic Controls," next.

MAJOR CLIMATIC CONTROLS OF THE SOUTHERN MOUNTAINS

The Kenya Highlands and Eastern Rift System. The mountains of the Kenyan Highlands and Eastern Rift System modify climate in the eastern portion of the region.

Wet Season. During the wet season, as low pressure develops over the continent, east-northeasterly flow from the Indian Ocean is orographically lifted into the eastern slopes of the mountains. Low clouds form by midday. Heating produces upslope winds on the western slopes; these converge with the prevailing easterly flow and lead to the development of scattered showers or thunderstorms during the afternoon. During the night, there is a downslope mountain breeze along the eastern slopes toward the coast; convergence between the mountain breeze and the seasonal moist easterly flow produces low-level cloudiness and showers along the slopes late in the night and early morning.

Dry Season. During the dry season, extensive stratiform clouds develop along the eastern slopes as moist south-southeasterly flow produces upslope cloudiness. Rainfall is rare; the strong inversion associated with the Southeast Monsoon prevents convection. However, during the evening along the higher elevations of Mt. Kenya and Kilimanjaro and the ranges that extend westward from them, south-southeasterly flow forced aloft begins to produce altostratus on the southern slopes. The development of the clouds is aided by the inversion, which lowers and intensifies due to diurnal cooling. This prevents the escape of the flow over the summits and generates higher surface winds in the already channeled flow. By 2200L, the surface winds strengthen, destroying any nocturnal radiational inversion and producing turbulence that increases low-level instability. These factors contribute to the thickening of the altostratus into nimbostratus. Embedded cumulonimbus forms near mountain summits as radiational cooling of cloud tops increases instability aloft and results in widespread continuous rain along the southern slopes, as well as thunderstorms (often severe) along the peaks. Rainfall lasts until 0700L, when the clouds begin to thin, dissipating by late afternoon. To the south of the ranges, thick stratocumulus or altostratus without rainfall forms during this regime, which occurs day after day during the Southeast Monsoon, but with decreasing rainfall amounts as the season progresses.

The Southern Highlands and Nyasa Rift System. To the south, the ranges of the Southern Highlands and Nyasa Rift System (including Lake Nyasa and the Shire River Valley) combine with the prevailing flow to produce a cooler, moist climate. The effects of the terrain are complex. Lake/land breezes and channeled winds from Lake Nyasa interact with the mountain ranges and the prevailing flow, causing unique diurnal variations.

Wet Season. During the wet season, this area is especially stormy, with profuse rainshowers and thunderstorms occurring day and night. Along the slopes that face the Indian Ocean to the east of the lake (and on the windward slopes of the Southern Highlands), prevailing northeasterly or southeasterly flow (depending on NET position) combines with valley breezes to produce upslope stratiform cloudiness during mid-morning; this lifts into cumulus by noon and develops into scattered rainshowers and thunderstorms during late afternoon. At night, mountain breezes down these slopes converge with the prevailing flow to produce clouds and occasional isolated thunderstorms. On the inner slopes surrounding Lake Nyasa, land/lake breezes also influence the climate. The lake breeze produces scattered afternoon rainshowers and thunderstorms on the slopes and escarpments, especially on the western side of the lake. At night, as downslope land breezes from the surrounding mountains converge over the lake, many thunderstorms and rainshowers form. They are most common over the northern end of the lake due to the convergence of land breezes from the west, north, and east. Toward the end of the wet season (March and April), thunderstorms and rainshowers are very active over the southern highlands to the northwest of the lake. Northward movement of the surface position of the NET at this time allows southeasterly flow to surge over the lake surface while there is still instability aloft. Orographic effects of the southeasterly flow are enhanced by the existing land/

lake breezes, setting off an abundance of thunderstorms, especially at night over the north end of the lake.

Dry Season. Dry-season conditions are more stable. With the prevailing southeasterly flow, convective activity rarely occurs. Low stratus develops in early morning, but usually lifts by 0900L. Fair weather cumulus is very common in the afternoon.

The Western Rift System is also affected by the combined effects of orographic lifting and land/lake and mountain/valley breezes. Along the mountain ranges that parallel Lake Tanganyika, daytime heating produces valley and lake breezes that ascend the slopes and help create cumulus clouds along ridge lines by late morning. Thunderstorms can develop by afternoon any time of year here, but especially during the rainy season. On many occasions, nocturnal land and/or mountain breezes can help regenerate thunderstorms over the lake at night. To the north of Lake Tanganyika in the mountains of Rwanda, Burundi, Uganda, and the adjoining area, orographic lifting occurs along the slopes that face Lake Victoria. Prevailing easterly flow picks up moisture as it passes over the lake, forming clouds and producing rainfall as it rises into the mountains. As mentioned earlier, northeasterly flow into this area picks up moisture as it passes over the swamps of Sudan, Lake Edward, and Lake Kivu; it produces cumuliform cloudiness as it is orographically lifted.

Lake Victoria. Situated at the equator, Lake Victoria has intense insolation, land/lake breezes, and a plentiful supply of moisture, all of which combine with topographic features to produce a variety of weather phenomena unique to the region. The eastern shore of the lake is in the rain shadow of the East African Highlands. Easterly flow descends the slopes of the mountain range, causing subsidence and less rainfall than the western shore.

Differential heating produces a lake breeze that usually begins around 1100L and results in subsidence and clear skies near the center of the lake. Thunderstorms and rainshowers form on surrounding shores and mountain slopes as convection, orographic lifting, and the lake breeze combine. The lake breeze also converges with the prevailing flow. The lake acts as a semipermanent low-pressure center that causes the easterly flow south of the lake to become southeasterly. Lake-breeze outflow converges with the large-scale east-southeasterly flow 150-200 kilometers east and southeast of the lake over the Serengeti Plain, causing a discontinuity line that can cause severe thunderstorms to move over the southern shore.

A land breeze, reinforced by mountain breezes off the surrounding slopes, forms over the lake during the night. Thunderstorms and showers develop over the center of the lake at night, as land breezes and large-scale easterly flow converge. These storms, caught up in upper-air easterly flow, move across the western shore during early morning. This diurnal wind circulation over the lake, combined with the large-scale flow during the Northeast Monsoon and the nearness of the Great Rift Heat Trough, produces enough rainfall to sustain the wet season between the "short rains" and "long rains," even though the NET has already pushed southward. During the dry season, prevailing flow is from the south, favoring the development of rainfall over the elevated terrain on the north side of the lake.

SPECIAL CLIMATIC FEATURES OF THE SOUTHERN MOUNTAINS

Mesoscale Systems. Several mesoscale systems influence the climate of the Southern Mountains, including the Great Rift Heat Trough, the Zaire/Zambian Low, the Congo Air Boundary (CAB), and the Chiperoni/Guti that occurs in the extreme southern portion of the region.

The Great Rift Heat Trough is a monsoon trough that lies over the western portion of the region from December to March. It is formed by convergence of Northeast Monsoon flow with South Atlantic High outflow and oriented generally north-south along the mountain ranges. The high terrain increases the lifting and convection while making the surface position of the trough less well-defined, but it is the active controller in the western part of the region during the height of the wet season.

The Zaire/Zambian Low. The effects of the Great Rift Heat Trough are enhanced by the Zaire/Zambian Low as it shifts along the trough during the wet season.

The Congo Air Boundary (CAB). The CAB is present in the western and southern portion of the region during the wet season. It normally remains semistationary across north-central Zambia, but surges can produce outbreaks of squall-line thunderstorms that move from northwest to southeast. The air behind the boundary is very unstable and moist.

The Guti and Chiperoni. The Guti of Zimbabwe and Zambia and the Chiperoni of Malawi are local names given to the extensive low-level cloudiness, fog, and drizzle that can occur at any time of the year and last for periods of 1 to 5 days. These phenomena are set up when transitory highs of cooler or cold air move out of South Africa and into the Mozambique Channel. Flow around the high-pressure cell advects cool, moist air from the Mozambique Channel into the Limpopo, Zambezi, and Shire River valleys. The air rises along the slopes of the highlands as it moves inland, reaching southeastern Zimbabwe and southern Malawi as a cold, nearly saturated air mass. Adjoining districts of Zambia are also affected, but less often.

Guti/Chiperoni invasions are normally associated with moderate to strong southeasterly winds that can gust up to 45 knots. Widespread stratus with bases between 500 to 1,000 feet can extend as far west as Bulawayo in Zimbabwe and the Muchinga Escarpment in Zambia (800 kilometers inland). Precipitation is generally in the form of drizzle, especially on slopes exposed to the wind. Clouds here are at their lowest and thickest, and orographic rain is frequent. Temperatures usually lower with the onset of the event, then remain steady (even at night) throughout the duration of the event.

During the rainy season, these disturbances are often preceded by squall-line thunderstorms that can develop 150 kilometers ahead of the boundary of moist southeasterly flow. Stratus associated with these phenomena is usually thicker and more persistent than in the dry season, since instability and the presence of higher clouds prevents burn-off from occurring. The tops of the stratus are generally lower during the dry season, and they don't last as long. Most events tend to occur in the morning, with lifting or a complete clearing likely by afternoon.

General Weather. The near-continuous wet-season convection over the zone brings abundant moisture to the middle and high levels. With so many additional sources of moisture at the surface, the result is one of the cloudiest regions in the world. As the NET moves southward, precipitating the onset of the Northeast Monsoon, the wet season begins in the northern portion of the zone with the so-called "short rains" that continue their southward movement until mid-December, when the NET reaches its southernmost position. The wettest areas are the northern tip of Lake Nyasa, the Lake Victoria basin, the windward sides of the Kenya Highlands, the windward slopes of Mount Kilimanjaro, northern and northeastern Tanganyika, and the Southern Highlands. Abrupt outcroppings on the flatter plains also receive higher rainfall than the surrounding area, resulting in widespread variability from one location to the next.

Moist air is advected into northeastern Zambia and Malawi from across the Indian Ocean by northeasterly surface winds. Drier southeasterly winds are often found *above* the northeasterly flow, aiding in the development of strong thunderstorms. Continuous rains over the region develop due to the convergence of cool air from the southeast with overrunning warm (Congo) air from the northwest.

Large areas of convection develop along the lakes in clusters or lines throughout the season. On its northward return, the NET causes the "long rains" over the northern portion of the region; southerly flow may produce orographic showers in the south. Thunderstorms are very frequent, occurring on 10 to 25 days a month.

Sky Cover is mostly from cumulus and cumulonimbus with bases at 1,500 to 3,000 feet. Ceilings are lower with rainfall, as ragged stratus clouds form below cumulus bases and sometimes reach the surface. Early morning stratus or stratocumulus often forms near lakes, marshes, and river valleys with bases below 1,000 feet. Early morning stratus and stratocumulus, with bases near the surface, are also common on the windward sides of mountain ranges.

Mean sky cover increases southward in connection with the seasonal position of the NET (Figure 9-2). Most ceilings are due to the heavy cirrus blow-off from thunderstorms. Most ceilings are above 3,000 feet (as shown in Figure 9-3), but there are exceptions that include Nairobi, where morning stratocumulus forms, and Songea, which is on a windward mountain slope.

During the wet season, scattered to broken altocumulus with bases at 10,000 to 20,000 feet and tops to 23,000 feet forms during early morning and breaks up by noon. Low cumulus develops by late morning. As heating continues, strong convection often results in cumulonimbus or towering cumulus by afternoon or evening, with tops to 40,000 feet. By late evening, all that remains of convective activity is altostratus with bases at 10,000 to 20,000 feet and thin cirrus with bases near 30,000 feet.

On occasion, overrunning produces widespread nimbostratus with bases as low as 1,000 feet and tops layered as high as 30,000 feet. Cumulonimbus may be embedded within the nimbostratus. These conditions may last up to 3 days.

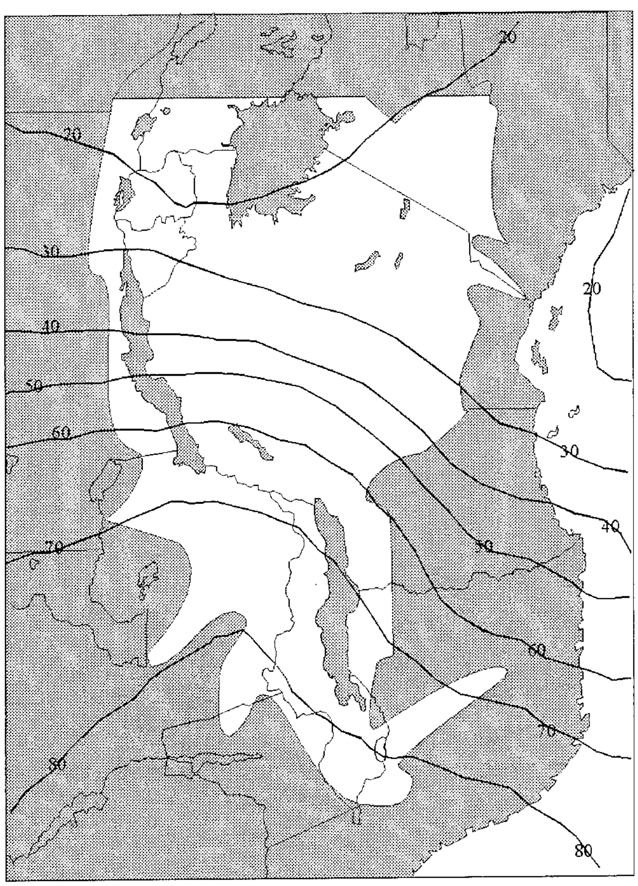


Figure 9-2. January Percent Frequencies of Ceilings.

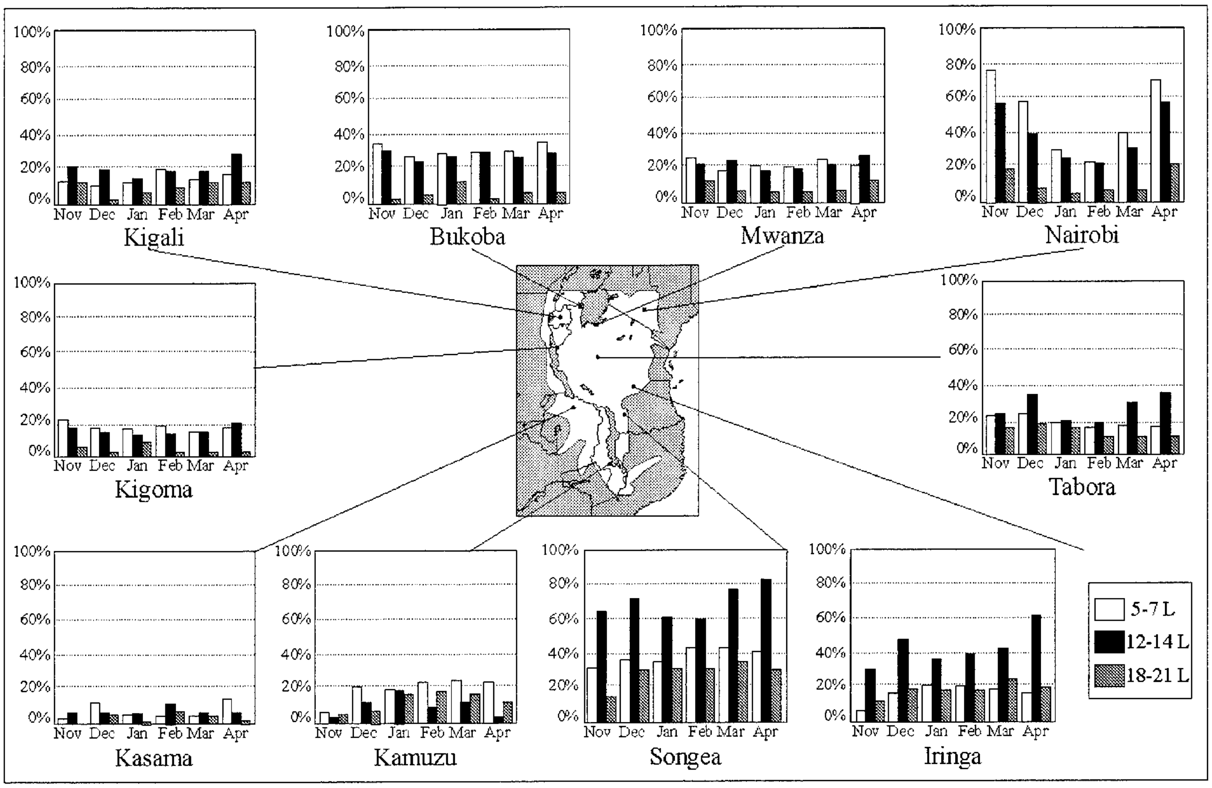


Figure 9-3. Wet-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Although visibility restrictions during the wet season are common, they are normally short-lived. Visibility is rarely below 1,600 meters. Most restrictions are caused by early morning radiation fog over areas that have received rainfall the previous day or, more frequently, upslope fog on windward sides of mountains. The fog quickly lifts or dissipates as soon as the sun rises, and rarely lasts for more than 1 or 2 hours. At Nairobi, fog forms most often in December between 0200 and 0500L, peaking at 0400L. Surface temperatures most favorable for fog are from 12 to 16° C. Fog forms with wind speeds from calm to 6 knots, but 4 knots is the most favorable. Favorable wind directions are between 10 and 80 degrees. Other stations along the mountains, such as Kigali and Kasama, also see morning fog. Heavy showers can lower visibilities temporarily to as low as 800 meters, but they improve rapidly as the showers pass.

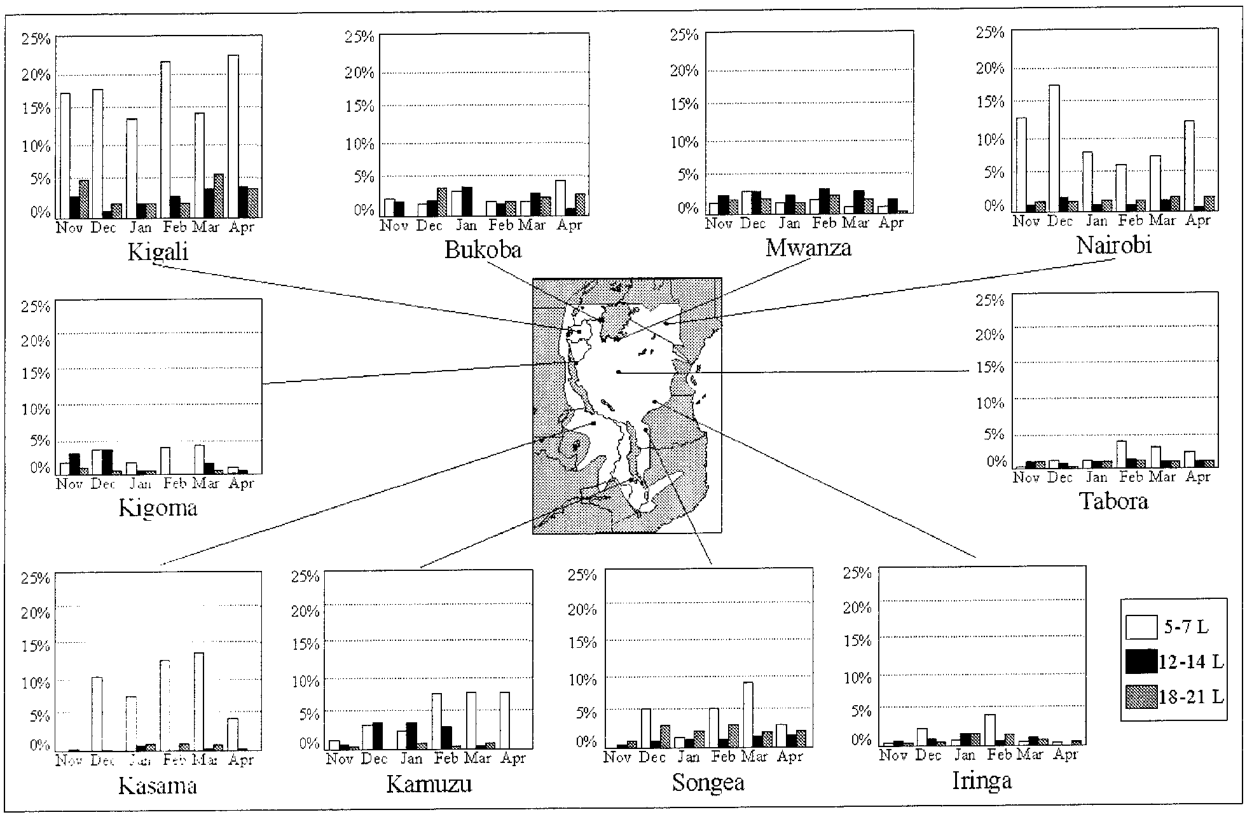


Figure 9-4. Wet-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. Wet-season (Northeast Monsoon) flow is generally northeasterly, from high pressure over the Arabian Peninsula to low pressure over southern Africa. Winds throughout the zone are influenced by the presence of semipermanent low-pressure troughs that include the one over Lake Victoria, the Great Rift Heat Trough, the Zaire/Zambian Low, and the Near Equatorial Trough (NET) These troughs create divergent flow over the central portion of the zone as segments of the flow split and track toward the troughs. The result is a large percentage of calm or light and variable surface winds over the interior.

Terrain also has a significant effect on the winds. Mountain-valley winds are common, overriding the prevailing flow in many cases. By diverting and channeling flow, the mountains also modify directions and increase speeds. Foehn-type winds occur on the lee sides of ranges. Lake effects are detailed in the discussion of "Major Climate Controls" at the beginning of this chapter.

In the northern half of the region, the Northeast Monsoon flow is usually first established at Nairobi during November (Figure 9-5a). It then moves southward behind the NET to about 12° S through November and December. The force of the Northeast Monsoon is usually light (5-10 knots). On the eastern slopes of the Eastern Rift System, the northeasterly flow can be channeled by terrain; directions can change and speeds can increase. South of the NET, winds are mostly easterly with slightly higher speeds (6-12 knots). Near the NET, winds are variable.

By February, northerly and easterly winds prevail (Figure 9-5b), except in the extreme south nearer the NET, where they are variable. The northwesterly flow at Kasama and Chipata is from the circulation of "Congo Air."

In April, prevailing flow becomes southerly and southeasterly over the southern portion of the region (Figure 9-5c), as the NET begins to recede to the north where, with the NET overhead, there is still a high percentage of calm winds.

With the high incidence of thunderstorms in and around mountains, mountain-wave turbulence is always a possibility. It is especially severe over the mountains on the western shores of the large lakes.

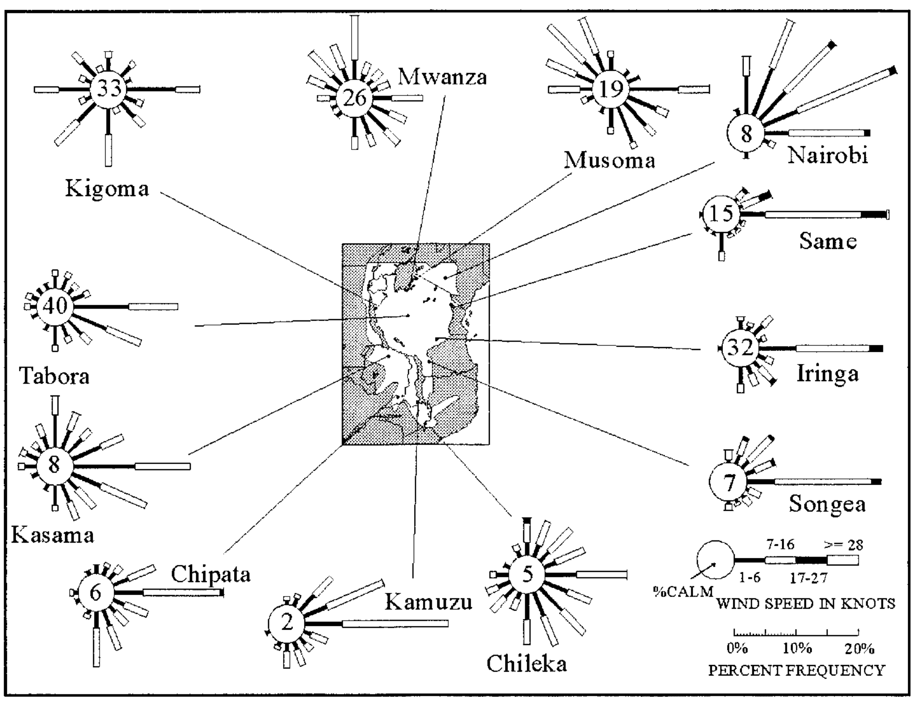


Figure 9-5a. November Surface Wind Roses.

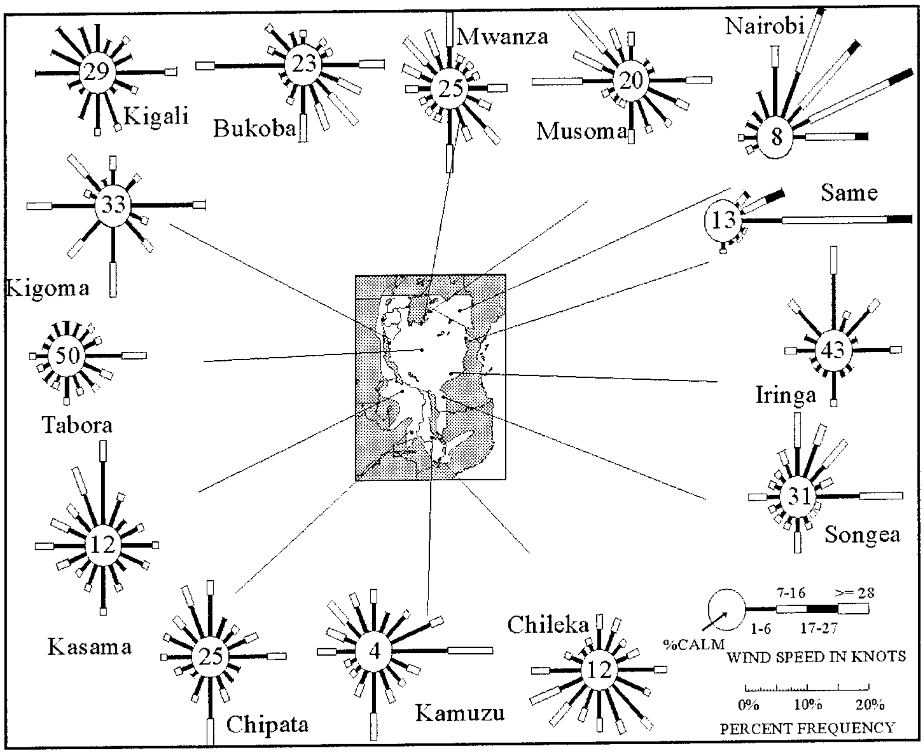


Figure 9-5b. February Surface Wind Roses.

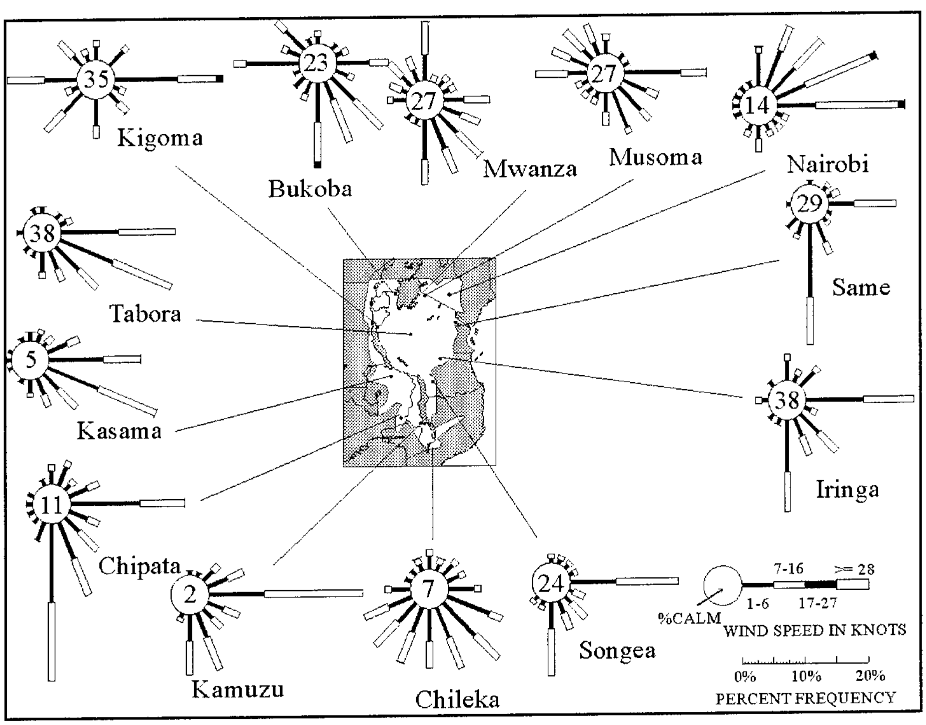


Figure 9-5c. April Surface Wind Roses.

Precipitation. Most rain falls as rainshowers and from thunderstorms, but snow can fall on mountain slopes above 4,800 meters MSL. On occasion, continuous rain caused by overrunning can fall for up to 3 days, but the highest amounts come from the heavy thunderstorms and showers that normally occur from 1100 to 1900L. Because of the showery nature of precipitation, rainfall amounts vary from year to year. As shown in Figures 9-6a, b, and c, however, most rainfall during the beginning of the season is concentrated in the north. By January, most of the rainfall is in the southern portion. By April, the heaviest precipitation has moved back northward, except along the northern shore of Lake Nyasa, where southerly flow is orographically lifted under conditions that are still unstable.

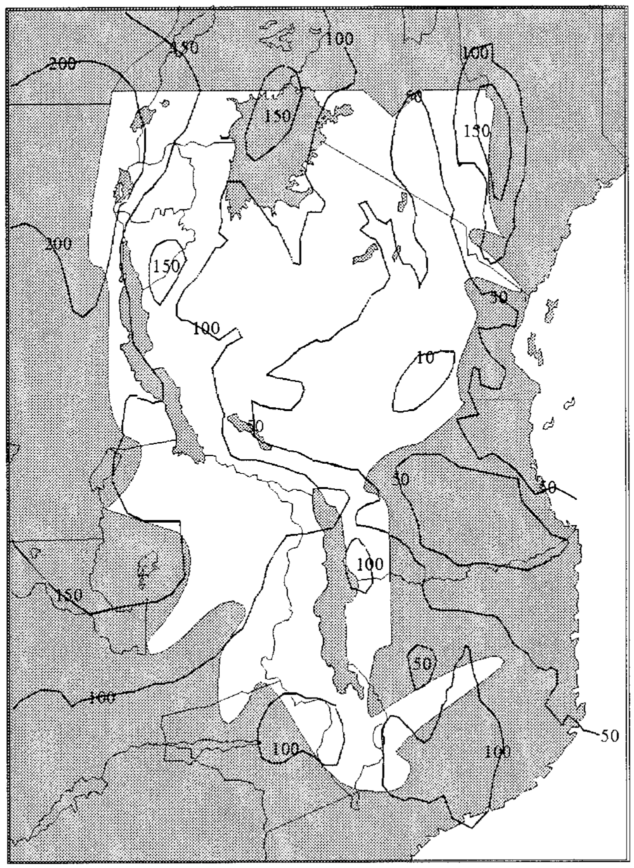


Figure 9-6a. November Mean Precipitation (mm).

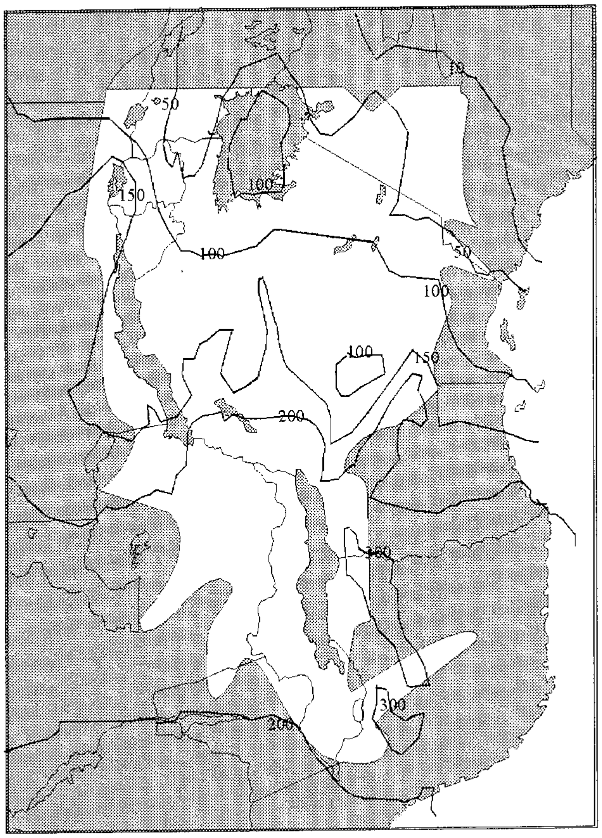


Figure 9-6b. January Mean Precipitation (mm).

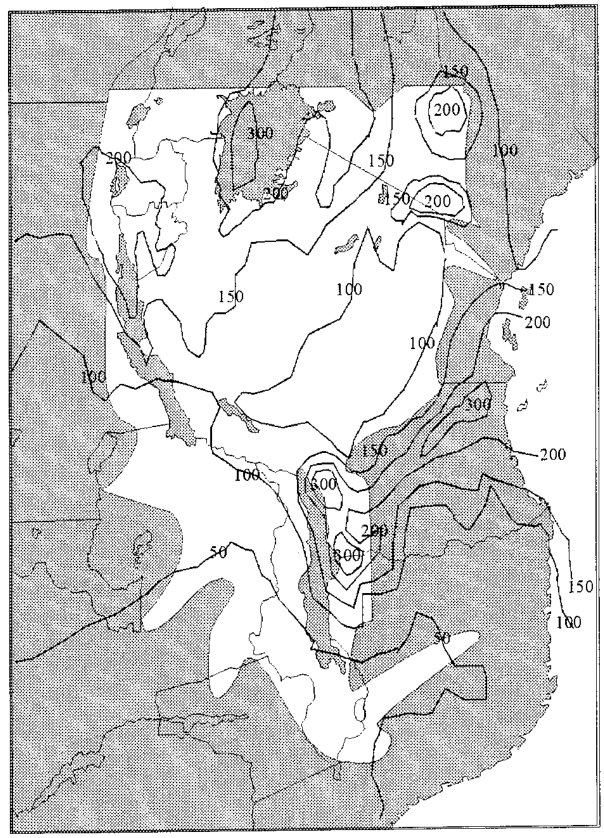


Figure 9-6c. April Mean Precipitation (mm).

Thunderstorms are common throughout the region. They are usually directly associated with the NET and/or orographic lifting. Associated wind gusts rarely exceed 35 knots, but speeds greater than 52 knots have been recorded. Thunderstorms tend to develop in lines or clusters that cover large areas, especially along Lake Tanganyika and Lake Nyasa. Tops are usually 40,000 feet, but they can reach 60,000 feet. At many locations, thunderstorms occur on as many as 15 to 20 days a month; see Figure 9-7.

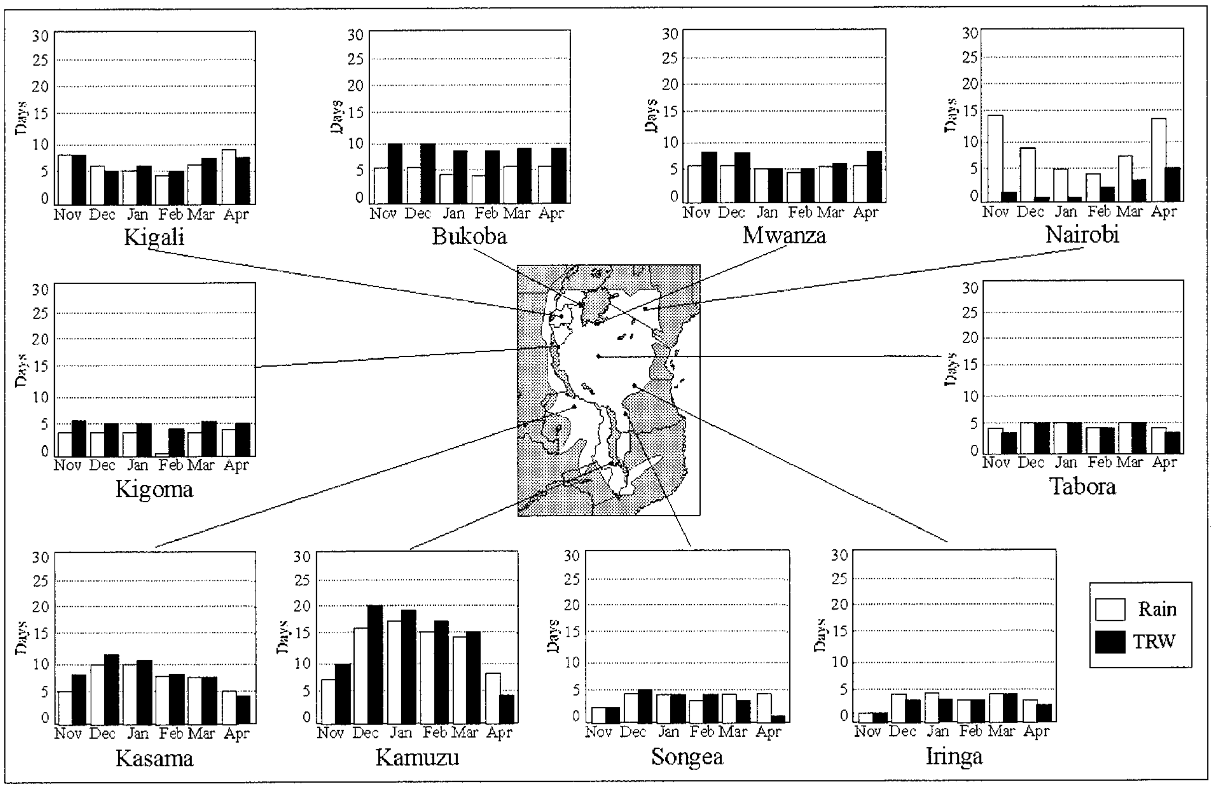


Figure 9-7. Wet-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Monthly variations in temperature are usually small, ranging from 1-2° C in the north to 5-6° C in the south (see Figures 9-8a and b). Elevation is the greatest variable. The wet season is the warmest over most of the region, with extremes as high as 40° C at stations in the rift valley. In the higher elevations, stations such as Nairobi have recorded highs that range from 33° to 20° C. Record lows range from near freezing on the peaks of Mount Kenya and Mount Kilimanjaro to 12° C in the rift valleys. There is permanent snow cover above 5,000 meters. Wet-bulb globe temperatures increase from 25° C in the northeast to 29° C in the Western Rift.

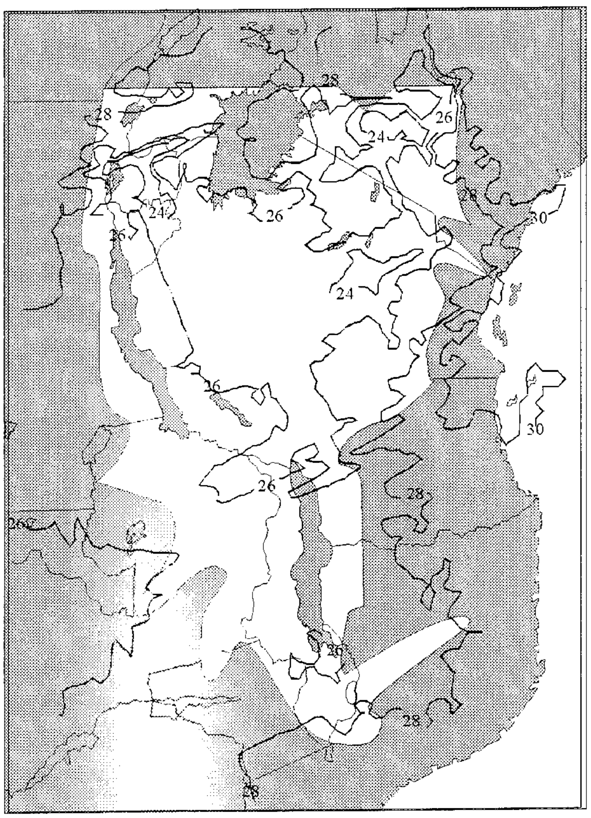


Figure 9-8a. Wet-Season Mean Maximum Temperatures (° C).

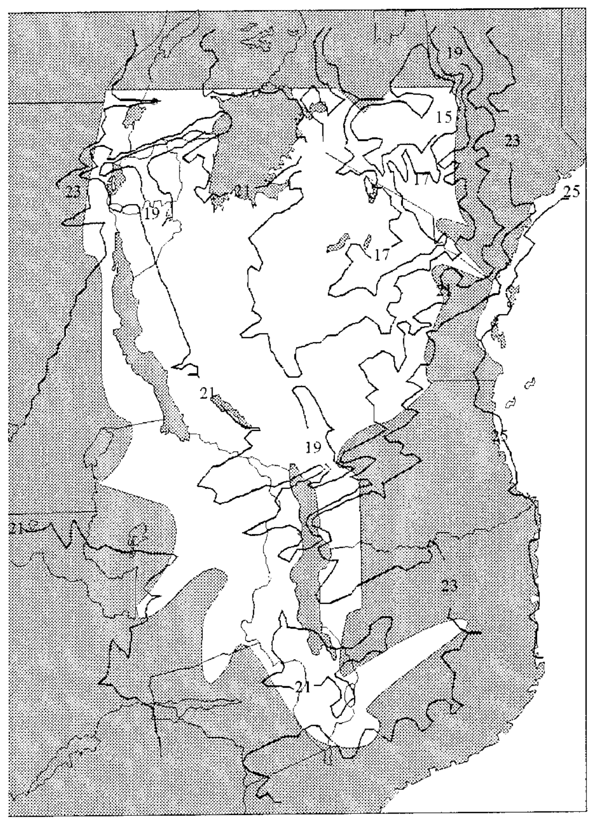


Figure 9-8b. Wet-Season Mean Minimum Temperatures (° C).

Other Hazards. Waterspouts and tornadoes occur only occasionally, but hail is much more frequent than in the dry season. Flash flooding can occur at any time, anywhere, but it is usually more significant where rainfall is typically low. Tropical cyclones may affect the southern portion of the region.

General Weather. The Southeast Monsoon dominates most of the region, resulting in a cooler, drier, and less cloudy dry season. A strong mid-level inversion and dry surface flow inhibit convective activity, which is limited to early May or late October and is dependent on the position of the NET.

Sky Cover. Fair-weather cumulus and widespread stratocumulus on mountain slopes are the most common clouds, normally less than 2,000 feet thick. Bases range from 1,000 to 5,000 feet. As shown in Figure 9-9, ceilings are most common in the Kenyan Highlands, usually from early morning stratus with bases near 300 feet. During the day, the stratus rises into stratocumulus ceilings with bases at 4,000 feet. The north and northwestern shores of Lake Tanganyika are also subject to low ceilings as southeasterly flow off the lake ascends the mountains and converges with moist "Congo Air." As seen in Figure 9-10, ceilings below 3,000 feet are uncommon in most of the zone, except along windward slopes facing the Indian Ocean.

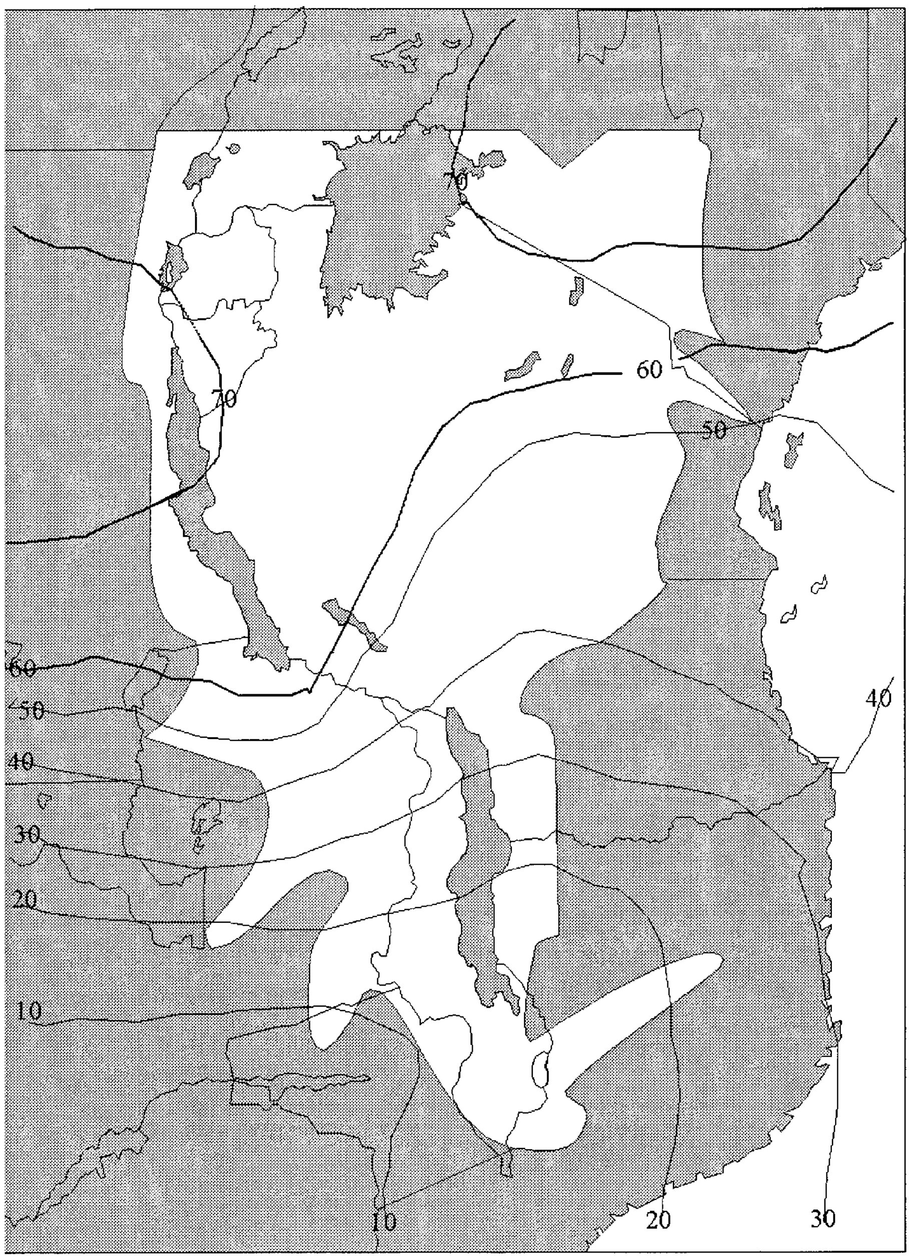


Figure 9-9. July Percent Frequencies of Ceilings.

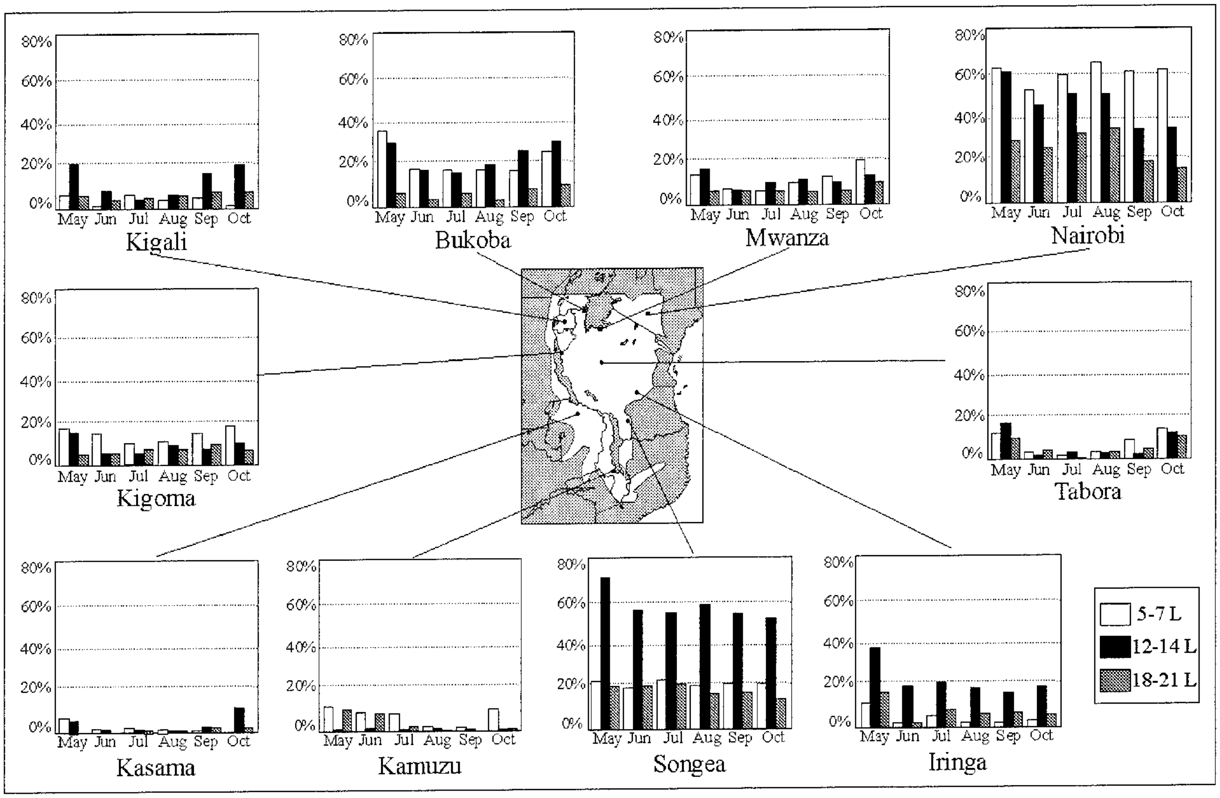


Figure 9-10. Dry-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Haze and suspended dust is common over the central plateau and across the plateaus of Rwanda and Burundi. Annual brush fires and volcanoes contribute to the haze, which can lower visibilities to 9,000 meters. Fog forms during early morning on the windward slopes of mountains and near lakes and swamps, normally from 0500 to 0800L; visibility is occasionally reduced to 1,600 meters. Lower visibilities are more common early in the season (see Figure 9-11). At Kigoma, on the eastern shore of Lake Tanganyika, visibilities are lowest in August, when southeasterly flow over the lake is at its strongest.

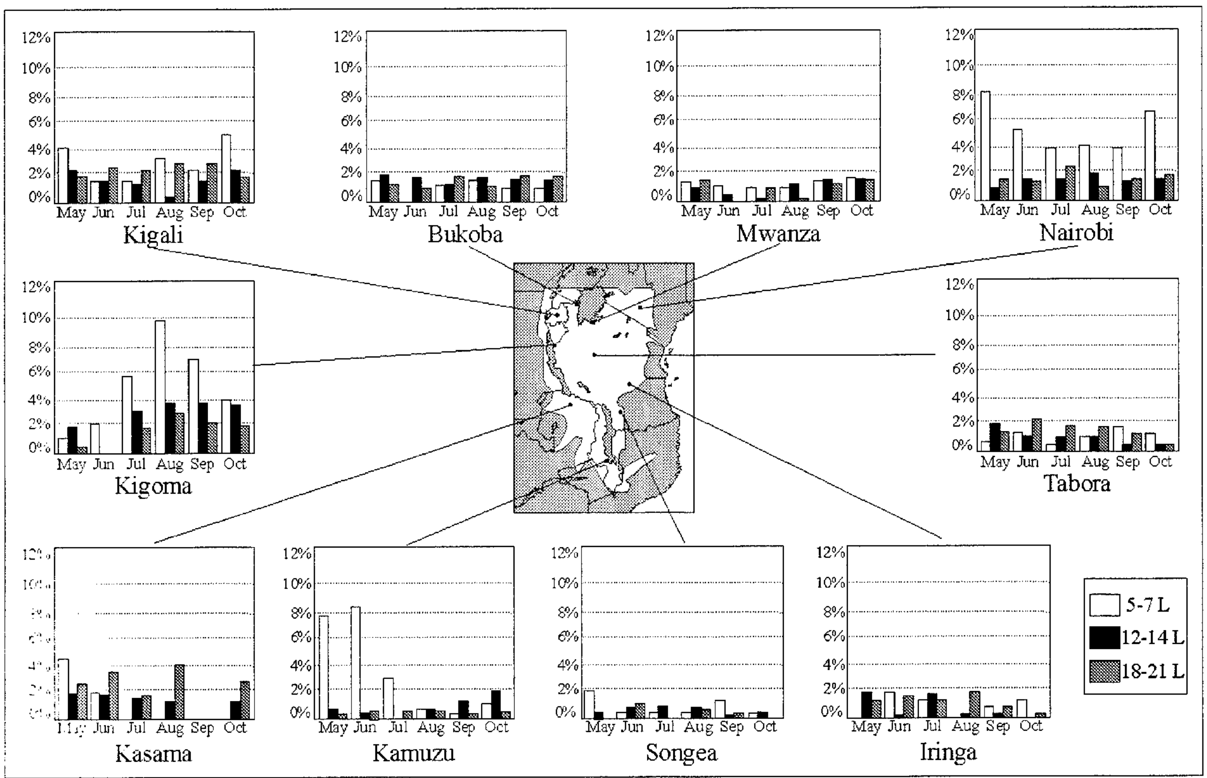


Figure 9-11. Dry-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. Dry-season winds are from the southeast at 5 to 15 knots during the day and at 3 to 8 knots at night (see Figure 9-12). The mountainous terrain can change the prevailing direction. Winds tend to become easterly as they diverge across the central plateau. Channeling of the flow, which increases speeds, also occurs in the mountains. Mountain wave turbulence is common. Mountain-valley and land/lake breezes (described in the discussion of "Major Climate Controls" at the beginning of this chapter) are about the same as they were in the wet season.

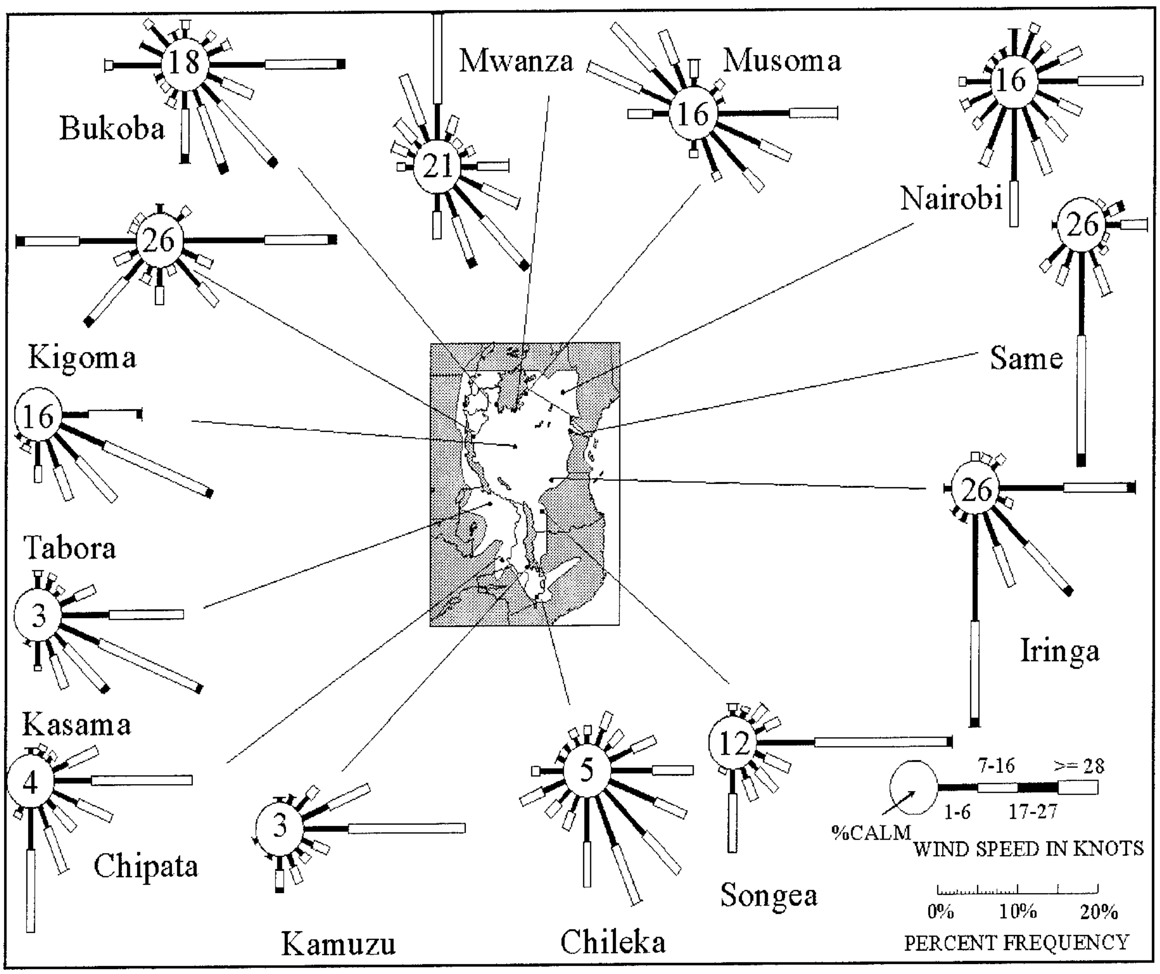


Figure 9-12. August Surface Wind Roses.

Precipitation. Although brief showers can still occur in the higher elevations and in the vicinity of Lake Victoria, rainfall is almost nonexistent by June, as shown in Figures 9-13 and 9-14. As the NET approaches during October, precipitation in the north begins to increase.

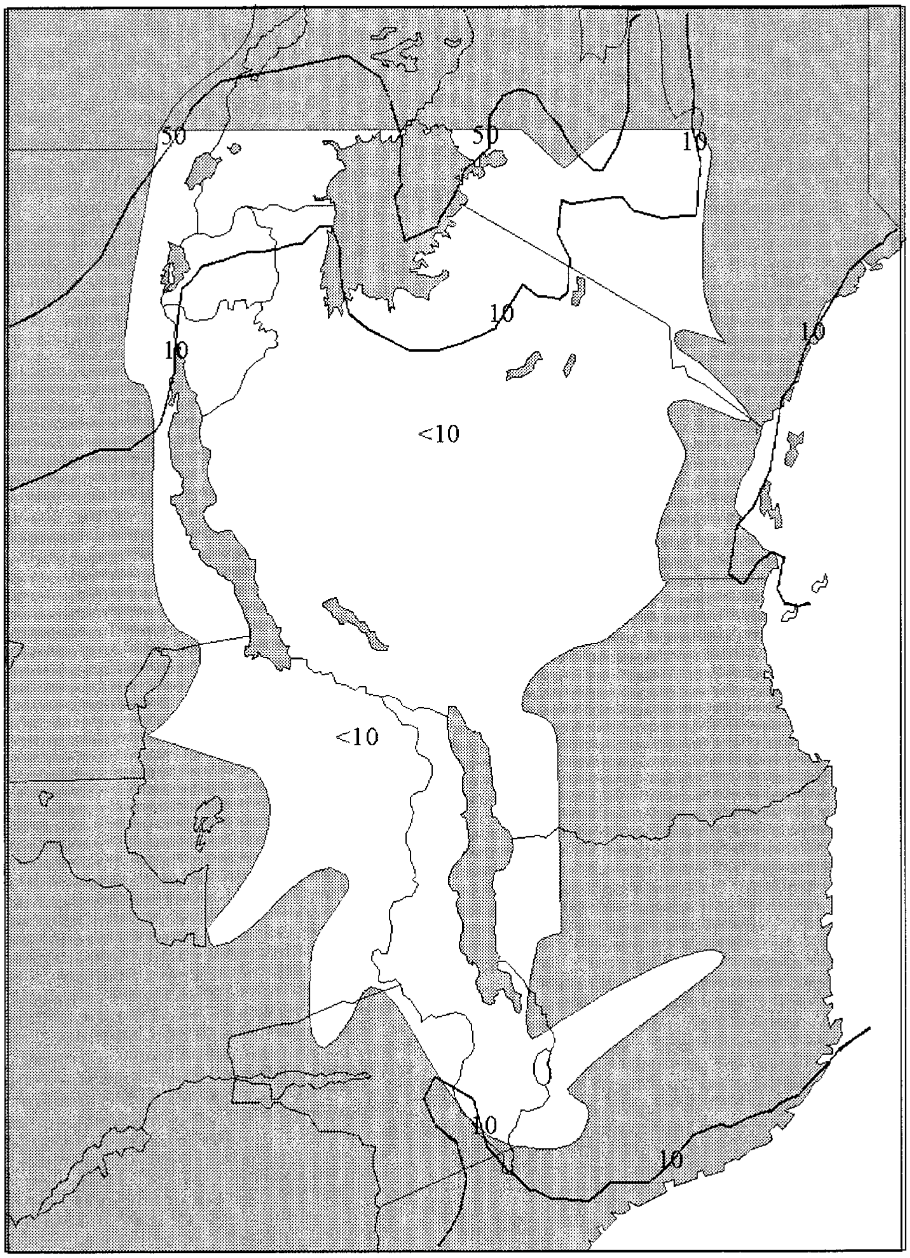


Figure 9-13. July Mean Precipitation (mm).

Thunderstorms are infrequent over most of the region from May to September, but frequency gradually increases to 4-8 thunderstorms a month by October. Tops can extend to 40,000 feet, with bases as low as 1,000 feet.

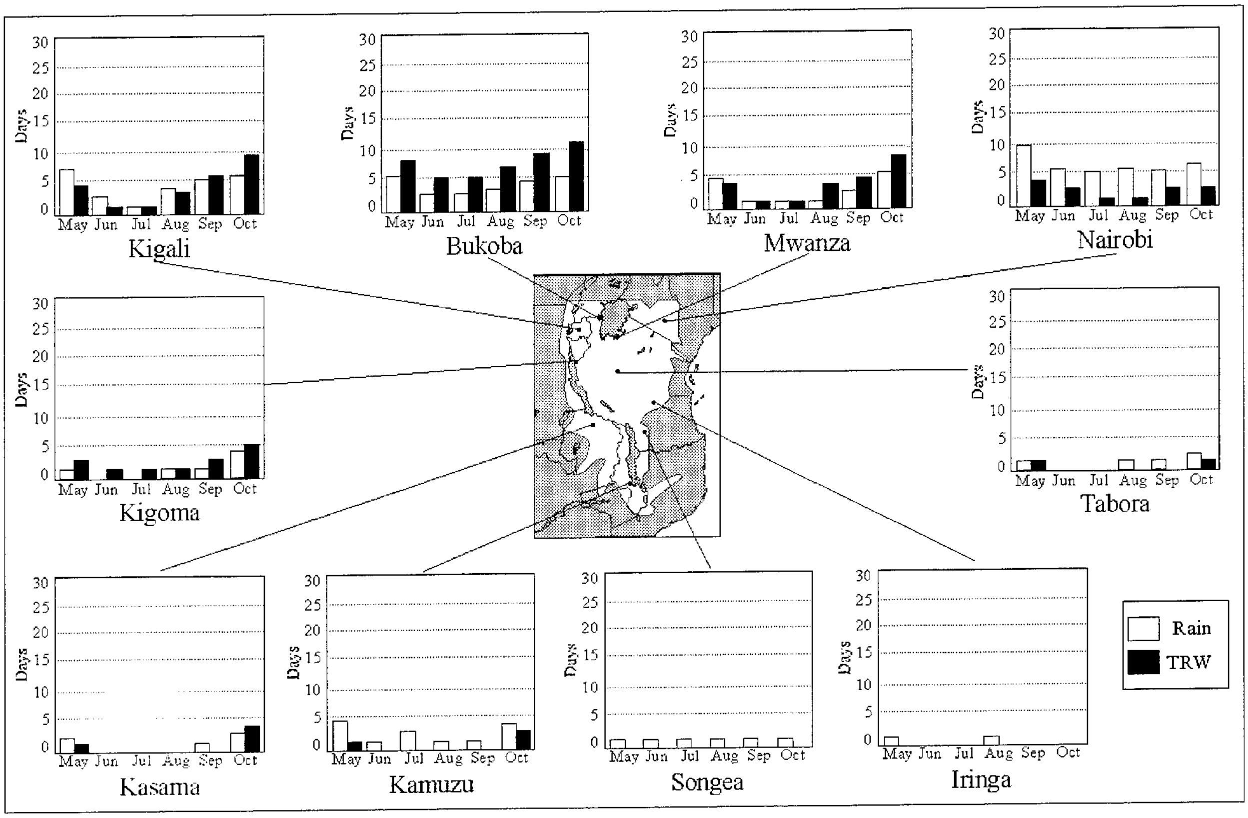


Figure 9-14. Dry-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Because the southeasterly flow originates (at least partially) from the continental South African High (see Chapter 2). Temperatures are lower during the dry season (see Figures 9-15a and b), Record highs range from 38° C at Kigoma to 32-35° C over the Central Plateau. Highs are only 29° C on the Masai Steppe, in the eastern and western rift systems, and in the highlands of Mawali. Record lows range from 3° to 11° C, but temperatures can be below freezing in the highest mountains. The snow line is between 5,000 and 5,100 meters. Wet-bulb globe temperatures range from 23° C in the northeast to 19° C in the southwest.

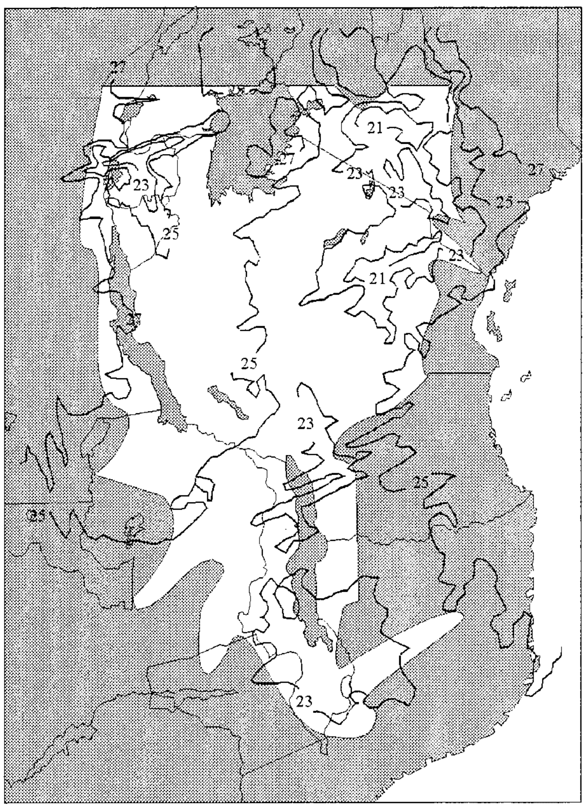


Figure 9-15a. Dry-Season Mean Maximum Temperatures (° C).

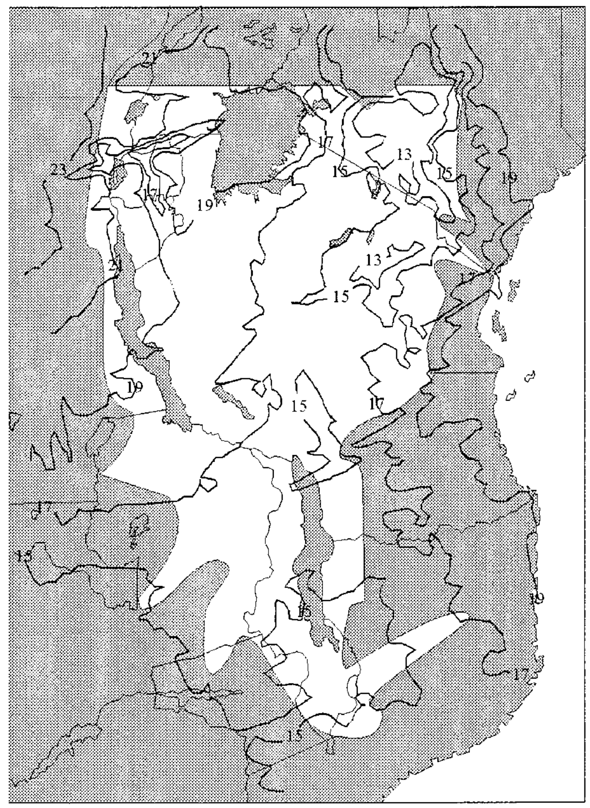
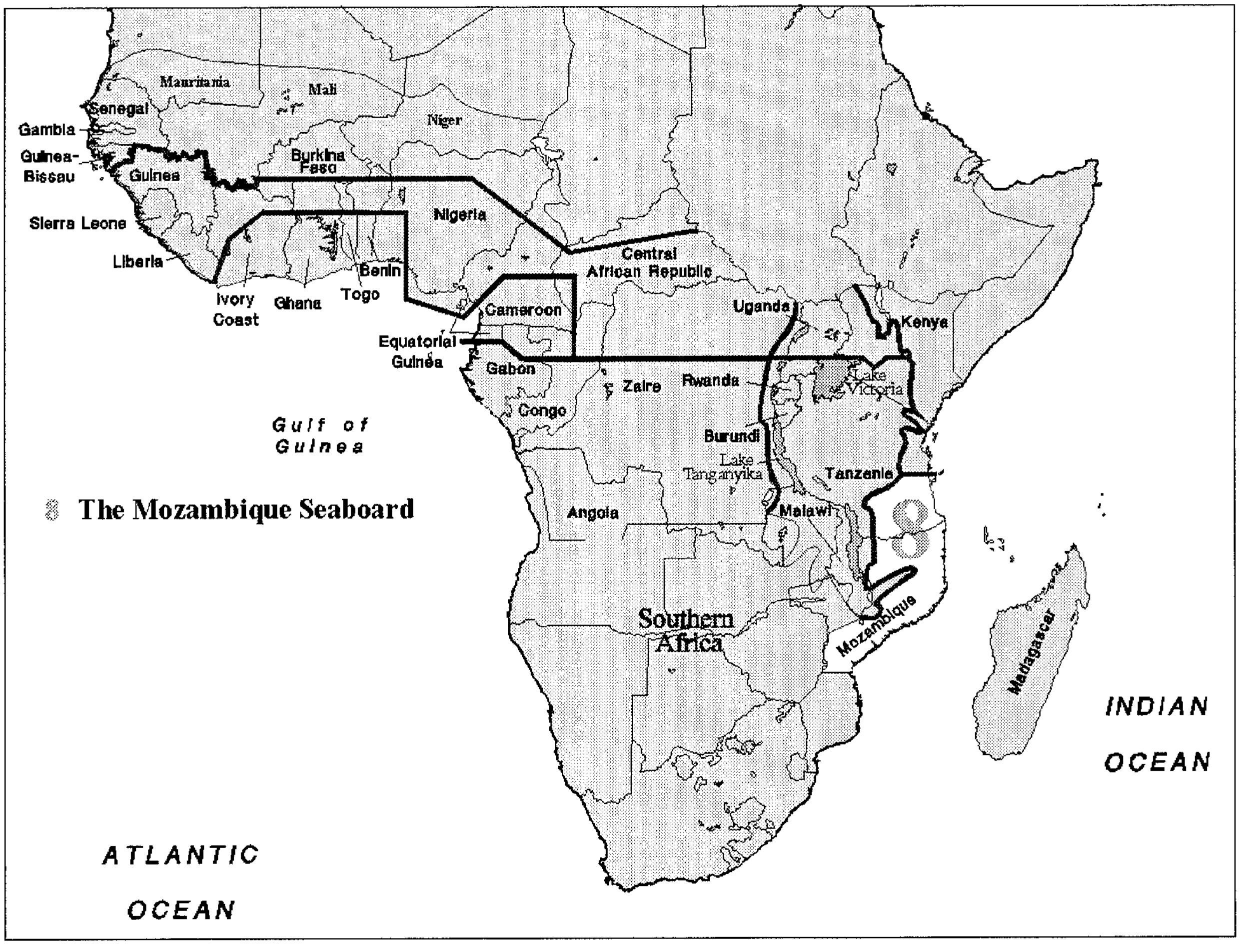


Figure 9-15b. Dry-Season Mean Minimum Temperatures (° C).

Chapter 10

THE MOZAMBIQUE SEABOARD

This chapter describes the geography, major climatic controls, special climatic features, and general weather (by season) of the Mozambique Seaboard, a coastal climatic zone that includes the southern portion of Tanzania and most of northern Mozambique.



MOZAMBIQUE SEABOARD GEOGRAPHY

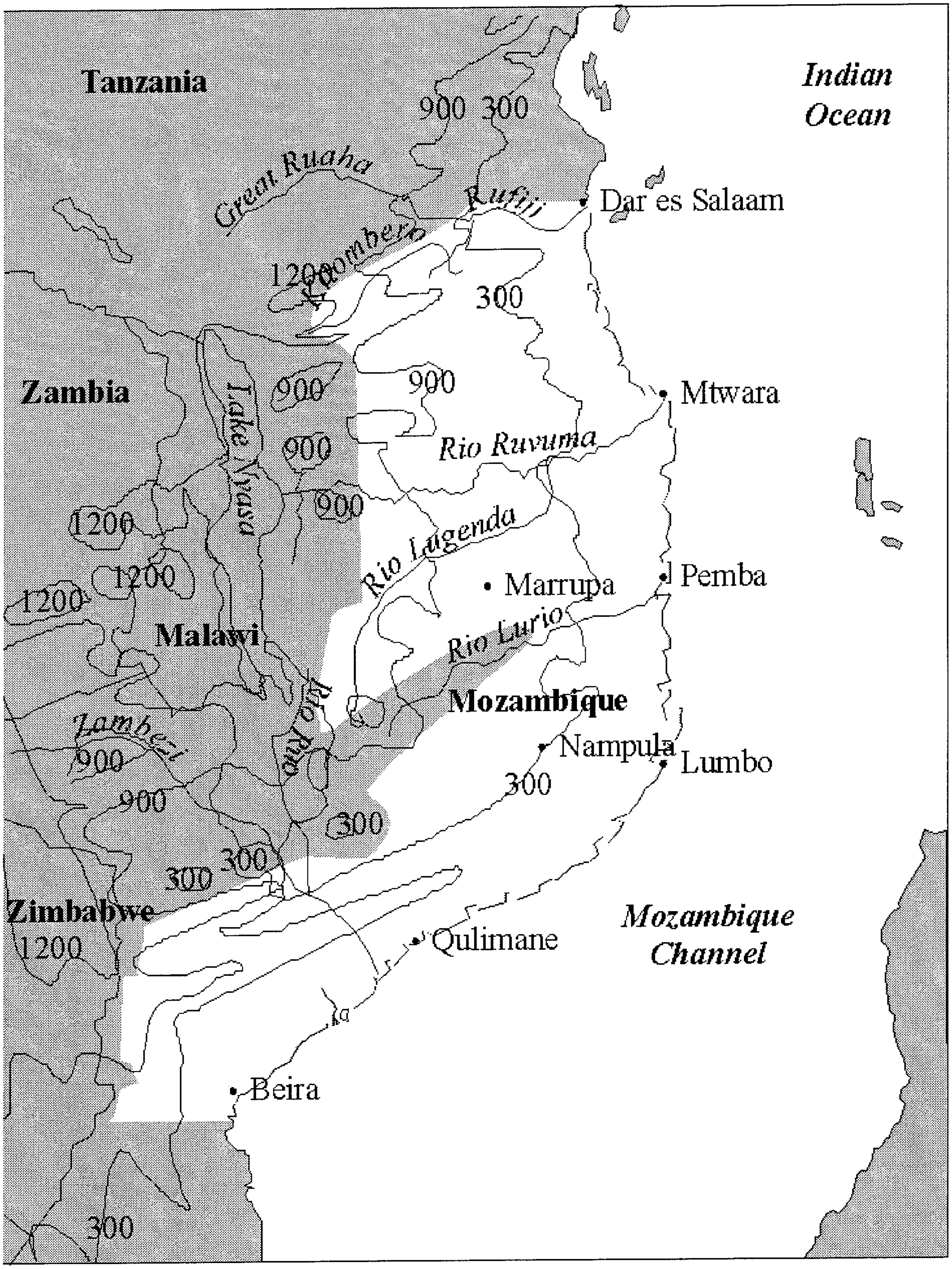


Figure 10-1. Topography of the Mozambique Seaboard. Contours in meters.

MOZAMBIQUE SEABOARD GEOGRAPHY

Seasons. The wet season (Northern Monsoon) runs from December through April; the dry season (Southern Monsoon), from May through November.

Boundaries. This coastal climatic zone is bounded on the east by the Indian Ocean and the Mozambique Channel. The northern boundary is marked by the limits of the December-April wet season and the May-November dry season. The western boundary is the 1,000-meter contour, except where the Zambezi River valley allows Indian Ocean moisture to be advected farther inland. The southern boundary is the southernmost limit of the Indian Ocean Monsoon Trough and the northernmost limit of the trade winds (20° S).

Major Terrain Features. The zone runs roughly northeast to southwest from Dar es Salaam to Beira. The immediate coast is mostly low-lying swamp, but in the northern portion, terrain rises west to a high plateau where elevations range from 200 to 500 meters. The Mozambique Channel lies between Mozambique and the island of Madagascar. The warm current through the channel flows from northeast to southwest the year-round.

Rivers. The Zambezi is the largest river in the area. It cuts across the southern portion of the area and empties into the Mozambique Channel between Beira and Qulimane. Several other smaller rivers also drain through the zone to the Indian Ocean.

Vegetation. Most of the zone is a scattered mix of grassland plains and deciduous forest. Northern Mozambique and southern Tanzania are characterized by broadleaf evergreen and deciduous forest, along with grassland. There are also grasslands in areas around the Zambezi River.

MAJOR CLIMATIC CONTROLS OF THE MOZAMBIQUE SEABOARD

The seasonal reversal of the winds is clearly defined in most of the zone. The Northern Monsoon brings the rainy season, while the Southern Monsoon brings the dry season.

The South Indian Ocean High and the Near Equatorial Trough (NET) provide the most direct influence on this coastal zone. The NET lies across the middle of the zone during southern-hemisphere summer, bringing the December-April wet season and heavy rains. During southern-hemisphere winter, the NET is located far to the north, producing a May-November dry season.

The climate of the Mozambique Seaboard is significantly modified by its tropical location and its proximity to the Mozambique Channel and Indian Ocean. Warm water currents, flowing northeast to southwest, parallel the coast all year. The effects of these currents are greater during the summer wet season than in the winter dry season. During the wet season, current speeds are increased by the prevailing northeasterly winds. The temperature of the current is about 25° C during the summer wet season, but only 19° C during the winter dry season.

General Weather. The Near Equatorial Trough (NET) lies across the center of the zone during the wet season, bringing frequent convection and heavy rains. The zone gets most of its 40 to 50 inches annual rainfall during the wet season. Tropical cyclones are possible, but infrequent.

Sky Cover. Wet-season cloud cover across the zone is extensive, with amounts increasing from north to south (see Figure 10-2). As moist air flows onto the continent from the Indian Ocean, the entire zone is affected. Mornings are generally overcast. In the afternoon, the overcast breaks up and cumulus develops, often resulting in isolated thunderstorms that dissipate after sunset. Bases vary between 1,000 and 3,000 feet. Low-ceiling frequencies increase toward the north and west (see Figure 10-3). At Quelimane, average cloud cover in December and January is more than 8/10 at 0900L, and only slightly less at 1500L.

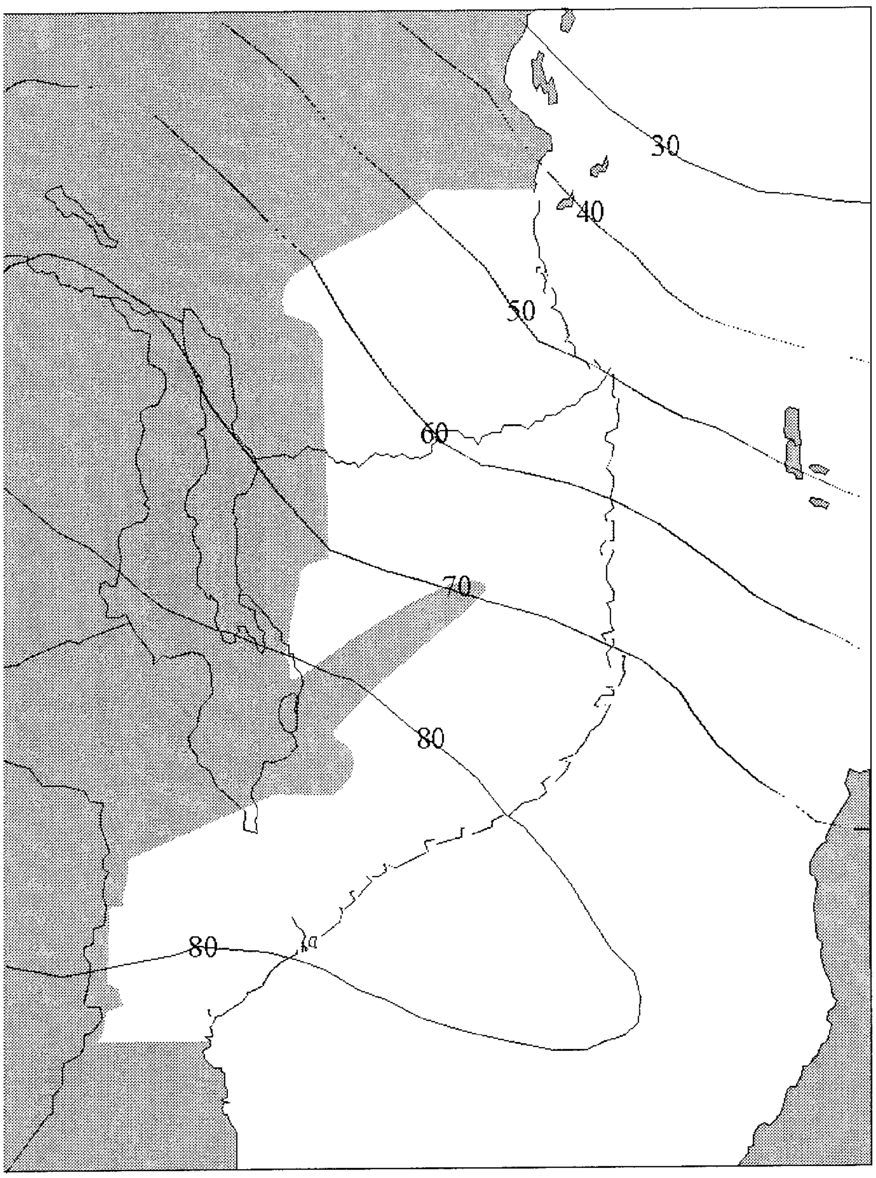


Figure 10-2. January Percent Frequencies of Ceilings.

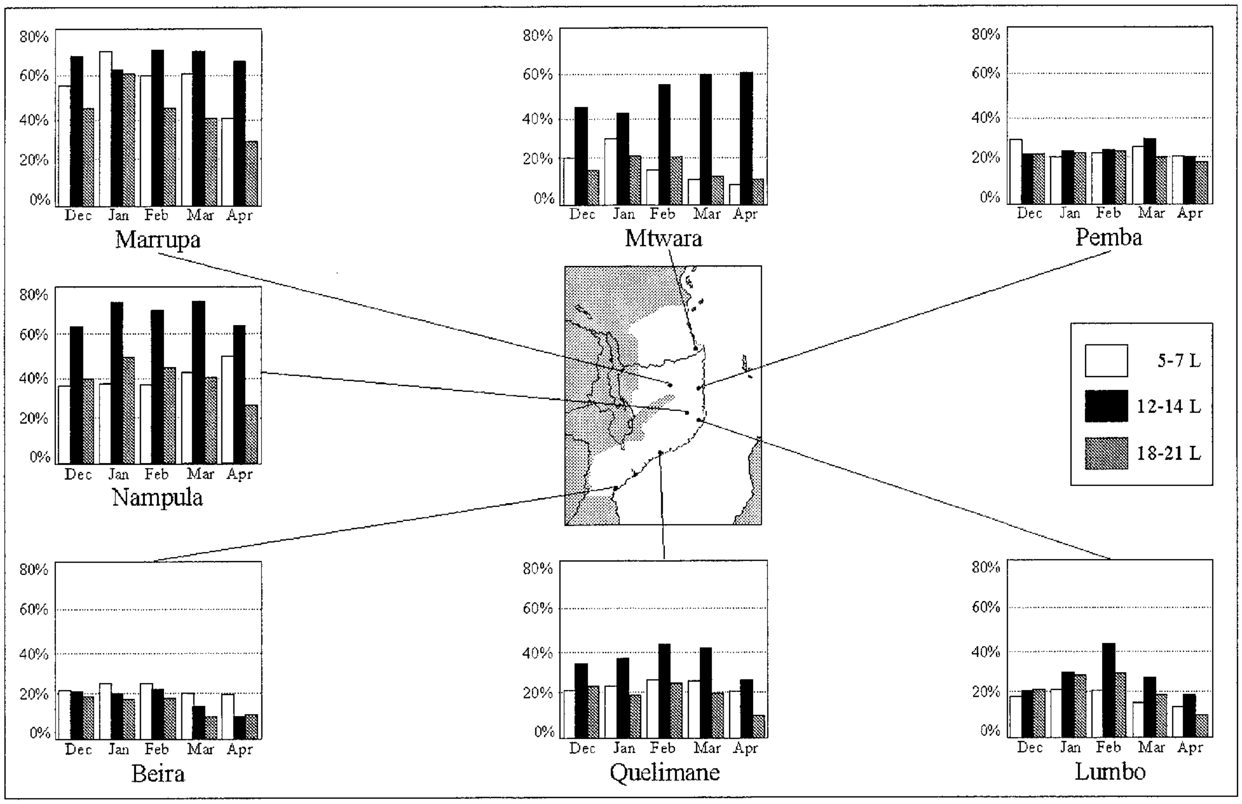


Figure 10-3. Wet-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Wet-season visibility is generally good, except for the morning fog that frequently forms overnight in areas that had rain the previous day, especially inland over the plateaus (see Figure 10-4). Heavy showers or thunderstorms can restrict local visibilities to less than 1 mile.

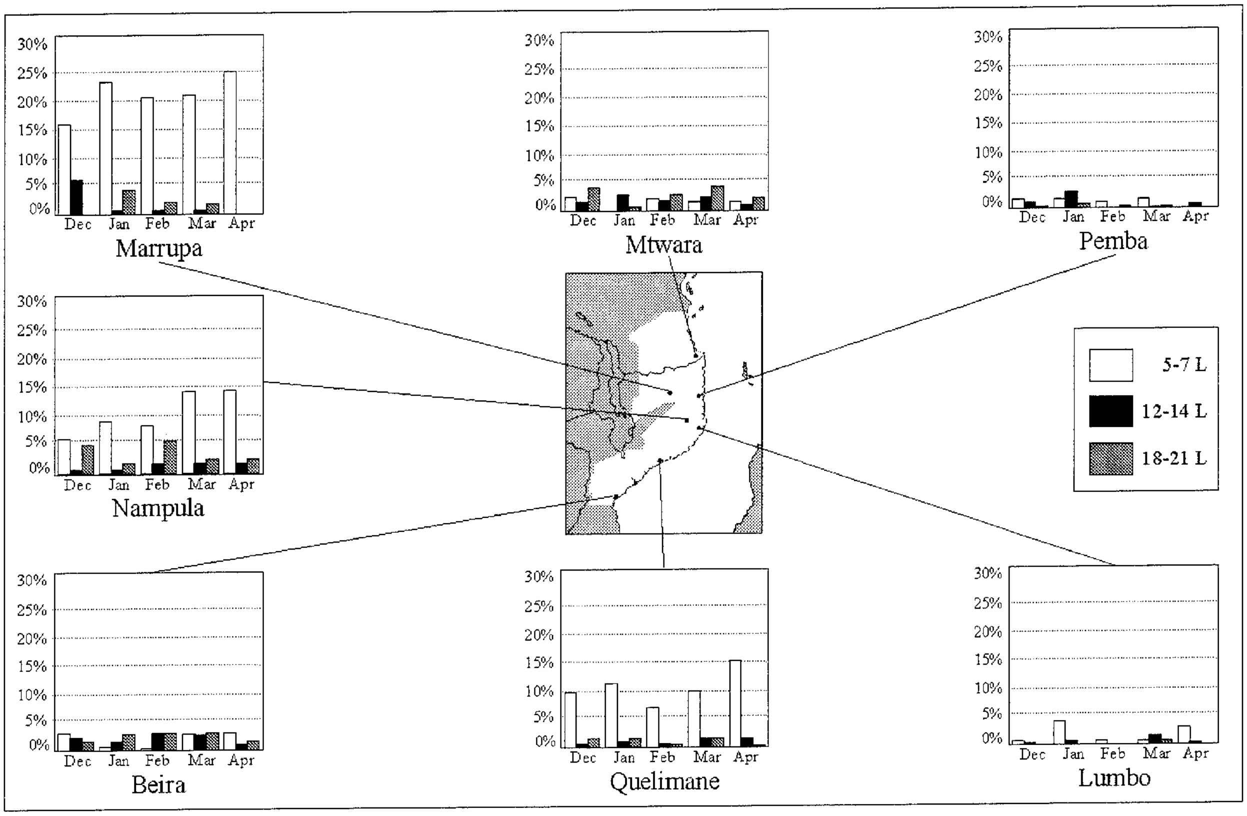


Figure 10-4. Wet-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. Except along the coast, wet-season surface winds have a distinct northerly component (see Figure 10-5). Speeds are usually 10-15 knots, occasionally gusting to 15-25 knots. There are occasional but rare gale-force (34 knots or more) winds in the Mozambique Channel.

Along the coast, surface winds have a well-defined diurnal variation because of the land/sea breeze. When pressure gradients over the coast are weak, a light westerly breeze usually blows during the early morning, shifting through north to northeast or east-northeast during the day. Differential heating between land and water introduces an easterly component by day (sea breeze) and a westerly component by night (land breeze). The easterly surface winds increase in strength to a maximum shortly after noon. The strongest winds usually occur in early afternoon; calms are most frequent at night and in the early morning.

Low-level turbulence occurs frequently over the plateau areas, where the surface warms rapidly during the day and sets up a turbulent exchange between heated air near the surface and cooler air aloft. By afternoon this convective overturning often shows up visually as towering cumulus.

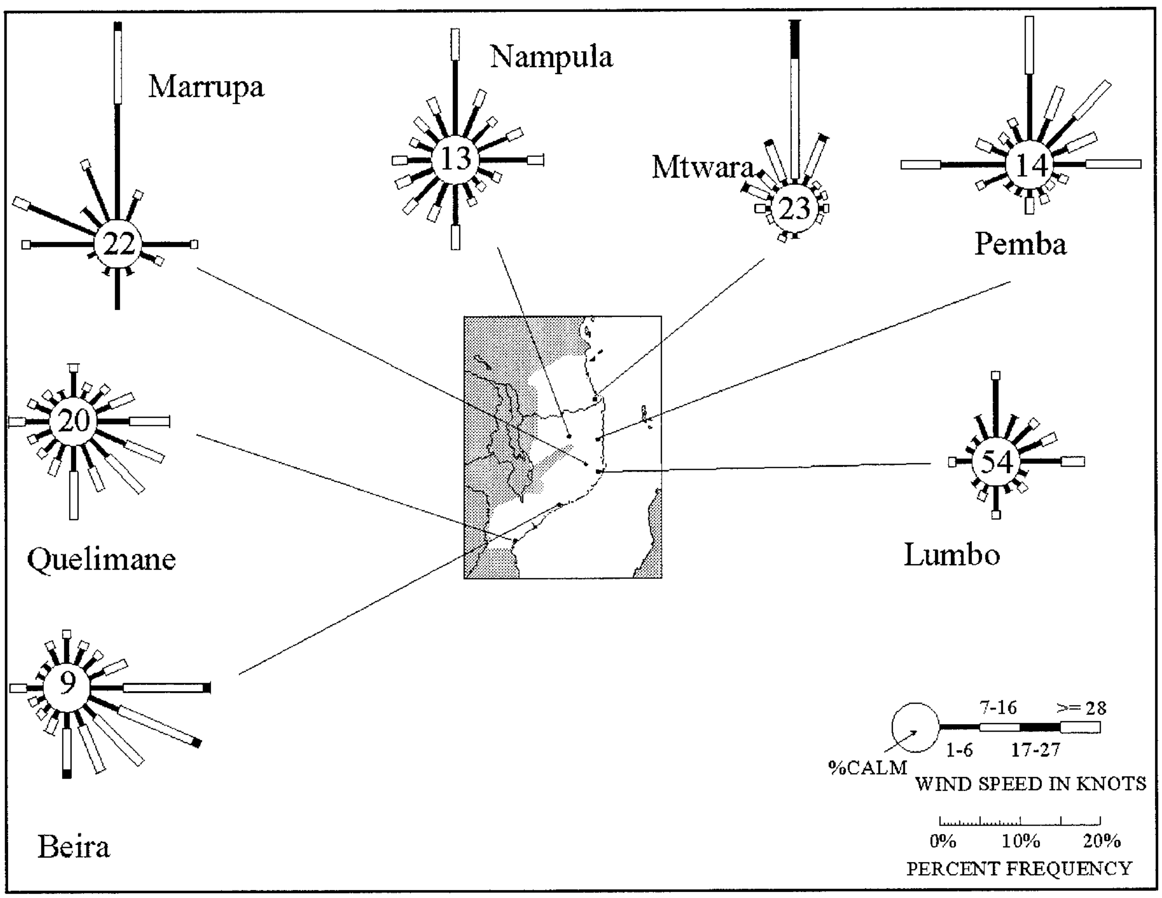


Figure 10-5. January Surface Wind Roses.

Precipitation. The Mozambique Seaboard gets from 1,000 to 1,250 mm of rainfall a year, most during the wet season, at a rate of 150 to 250 mm a month. On the coast, the heavy rains begin in December and last until April; February and March are the wettest. On the plateau, most of the rain falls from December through March. Most rain falls as showers or from thunderstorms.

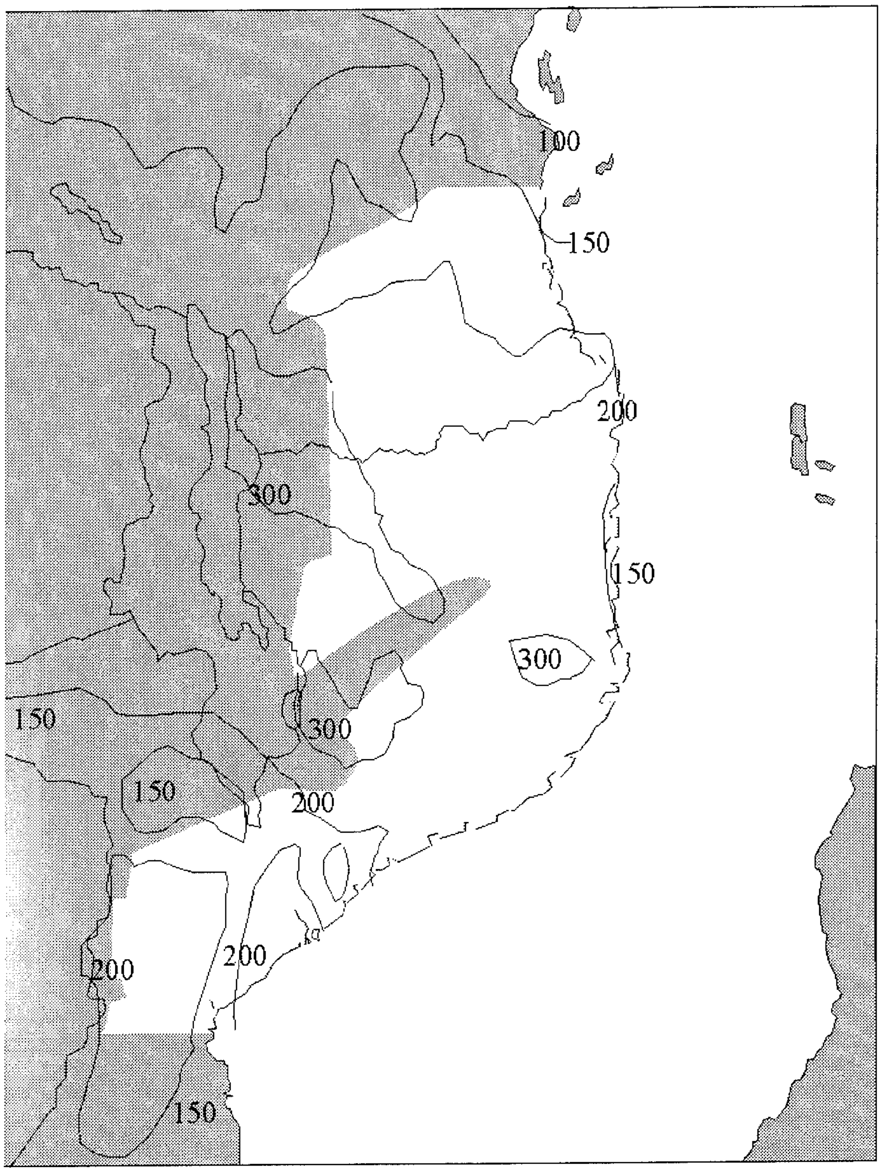


Figure 10-6. January Mean Precipitation (mm).

Thunderstorms. Wet-season thunderstorms are fairly common. They generally develop during the afternoon. Most stations have 5 to 10 days with thunderstorms each month of the wet season (see Figure 10-7). Severe thunderstorms with hail and high winds are possible; flash flooding can result.

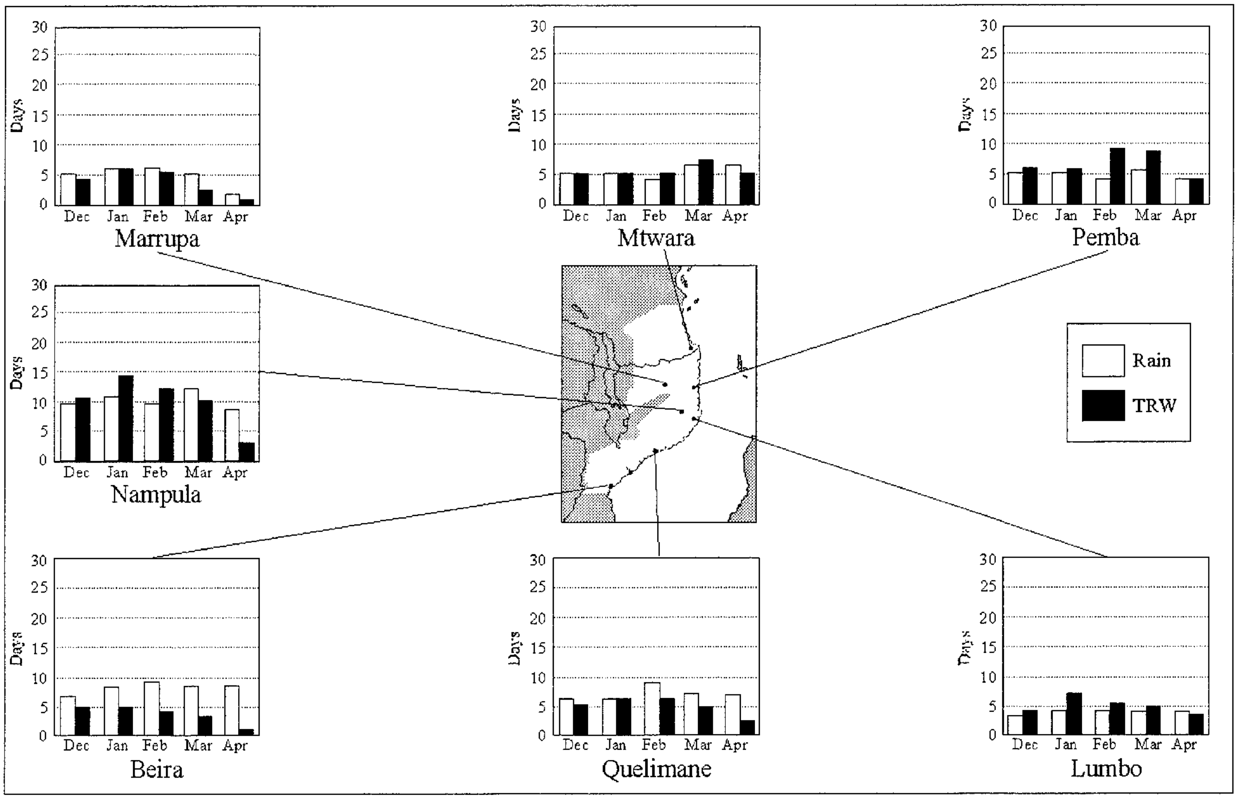


Figure 10-7. Wet-Season Mean Monthly Rain and Thunderstorm Days.

Temperatures. Temperatures are high the year round. Although coastal temperatures are moderated by the Indian Ocean, the coast is still slightly warmer than the elevated highlands. The southern half of Mozambique is influenced by the warm Mozambique Current that flows southward through the Mozambique Channel.

Average high temperatures are generally near 30° C, with normal lows in the mid 20s° C. At Quelimane, located on the southern coast, the extreme high temperature is 41° C and the extreme low 18° C. In the highlands, Marrupa has recorded extremes of 30° and 19° C.

Although relative humidities in Mozambique are high the year round, they are highest during the rainy season. Moisture is concentrated in the lower levels as the air begins to move inland. Heating from below causes a portion of this moisture to be distributed to higher levels and decreases the surface humidity. At night, cooling tends to raise relative humidities.

Average wet-bulb globe temperatures are from 30 to 31° C.

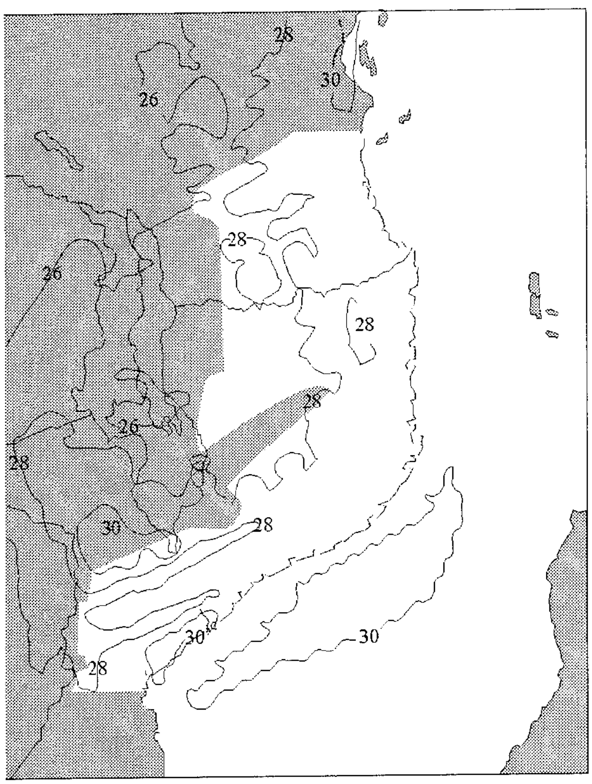


Figure 10-8. January Mean Maximum Temperatures (° C).

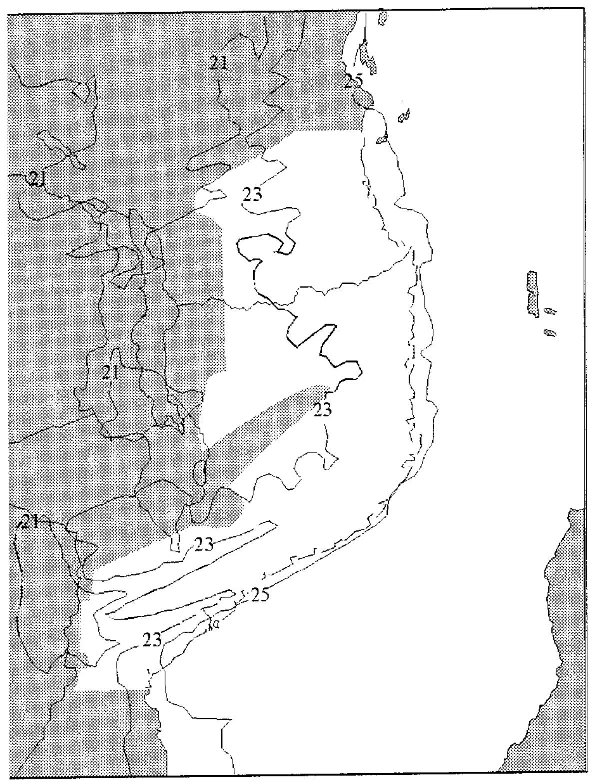


Figure 10-9. January Mean Minimum Temperatures (° C).

Other Hazards. Severe thunderstorms, with hail and high winds, can result in flash flooding the year round. Tropical cyclones occasionally but rarely affect the area. Those that develop in the Indian Ocean can move westward across Madagascar and the Mozambique Channel and onto the African continent over Mozambique. It is also possible for tropical cyclones to develop in the Mozambique Channel and move northeast into the Indian Ocean.

General Weather. During southern-hemisphere winter, the mean position of the NET moves northward along with the Indian Ocean High. The prevailing flow becomes southerly, moving drier air across the zone and into the highlands. There is very little rainfall during the dry season.

Sky Cover. Low stratus, stratocumulus, and nimbostratus are more common during the dry season (southern-hemisphere winter) than the convective clouds that dominate the wet season. Morning skies are overcast with low stratus clouds on about 1 day in 3. The stratus generally becomes cumulus by late afternoon and dissipates after sunset. Fair-weather cumulus and high thin cirrus are common. Low clouds from the Indian Ocean occasionally move inland, but bases are seldom below 1,000 feet. The low clouds that form over the lowlands at night dissipate shortly after sunrise.

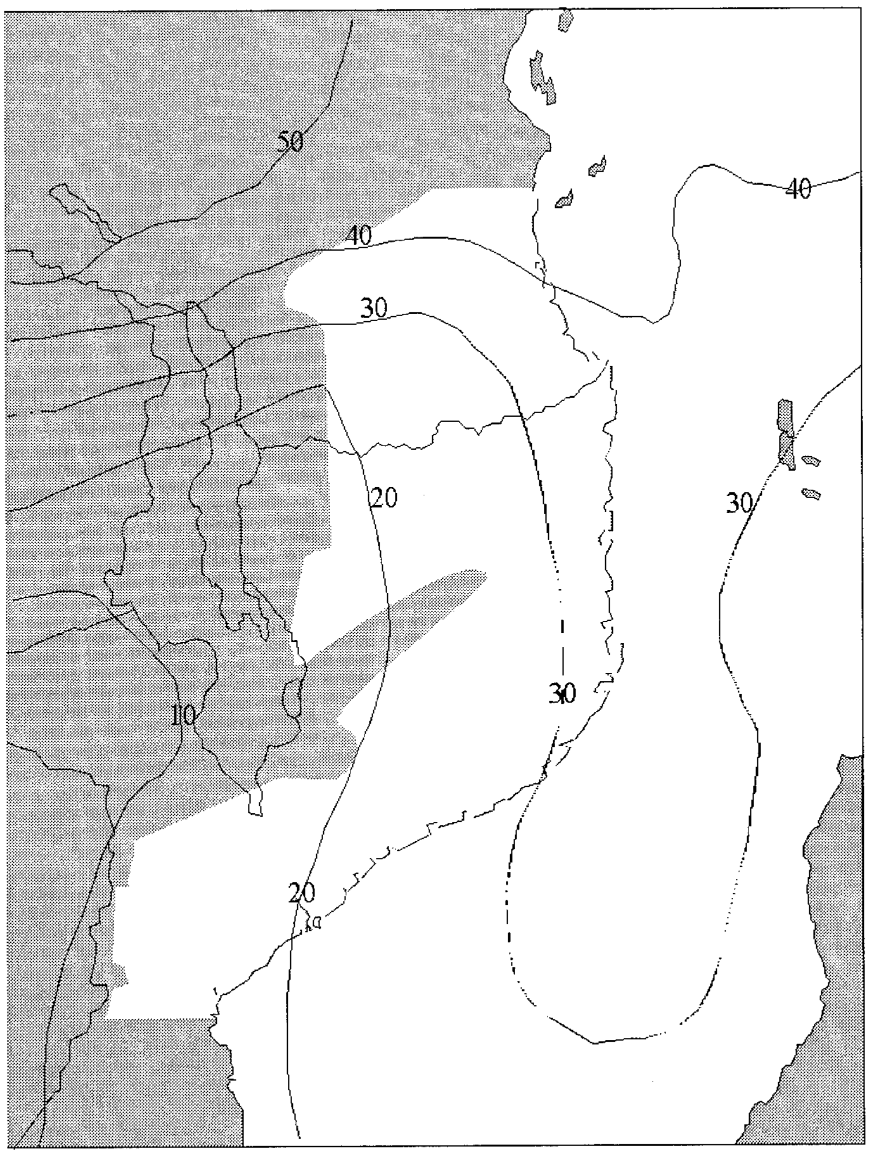


Figure 10-10. July Percent Frequencies of Ceilings.

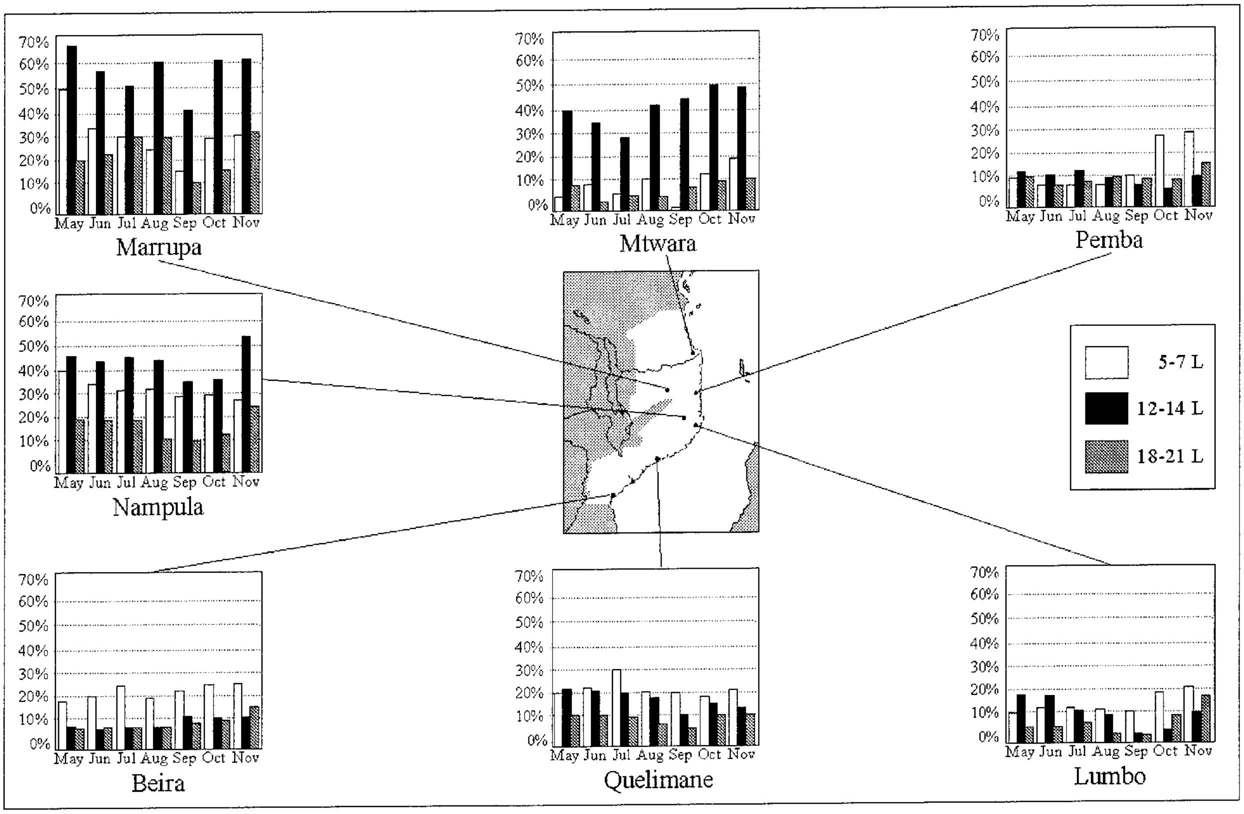


Figure 10-11. Dry-Season Percent Frequencies of Ceilings Below 3,000 Feet.

Visibility. Over the coast of Mozambique, visibility is generally good the year round. The best visibilities along the coast are in the transitional months of April and May (wet-to-dry) and October and November (dry-to-wet). The worst visibilities are in winter (from May through August) when there is thick haze in the river valleys, at sea close to shore, and on the mountain slopes in the west. This haze, known locally as the "Cacimbo," occurs on about 12 to 18 days a month in winter dry season, and on about 7 days a month in the summer wet season. The Cacimbo may reduce visibilities to as little as 2 miles, but it clears away soon after 0900L and visibility returns to normal. There is very little occurrence of fog along the coasts of this area. Dust is occasionally stirred up by unstable air in the heat of the afternoon. When the dust is carried aloft, it may remain in suspension for days.

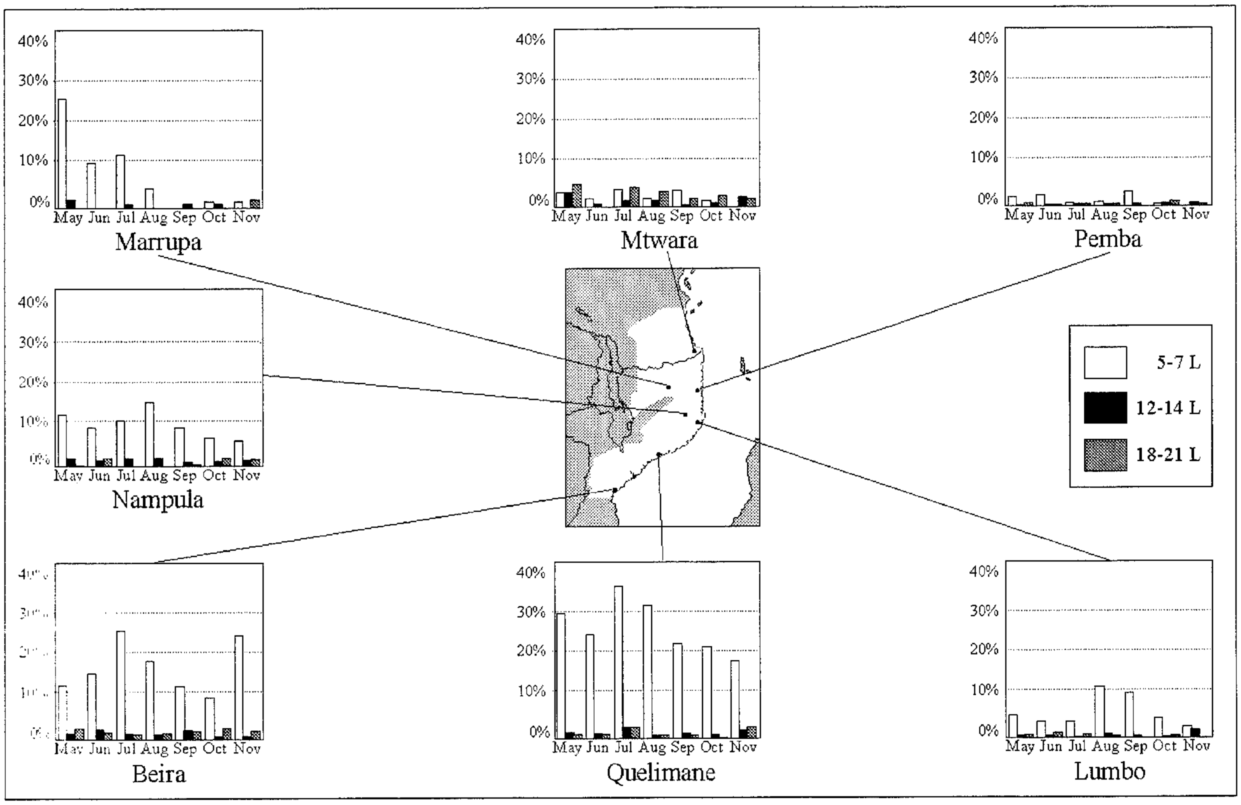


Figure 10-12. Dry-Season Percent Frequencies of Visibilities Below 4,800 meters.

Winds. Surface winds are generally southerly during the winter months, carrying drier air across the area (see Figure 10-13). Wind speeds are usually 10-15 knots. The land and sea breezes are generally not as pronounced as during the wet season, and are often overcome by the large-scale flow.

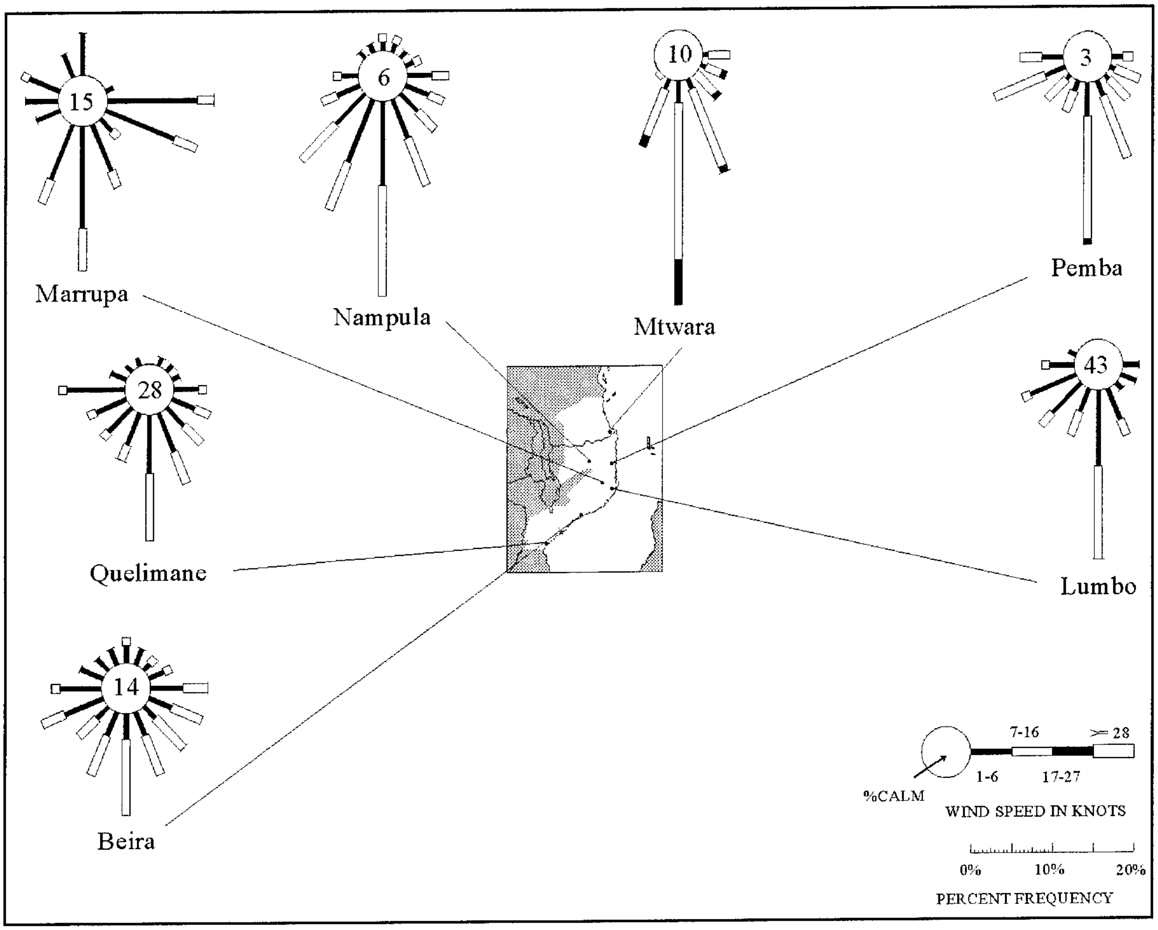


Figure 10-13. July Surface Wind Roses.

Precipitation. There is very little rainfall during the southern hemisphere winter (see Figure 10-14). The NET has moved north toward the equator and the low-level flow moves dry air into the region. Average monthly rainfall is 10 mm or less for most of the zone. Thunderstorms are extremely rare (see Figure 10-15).

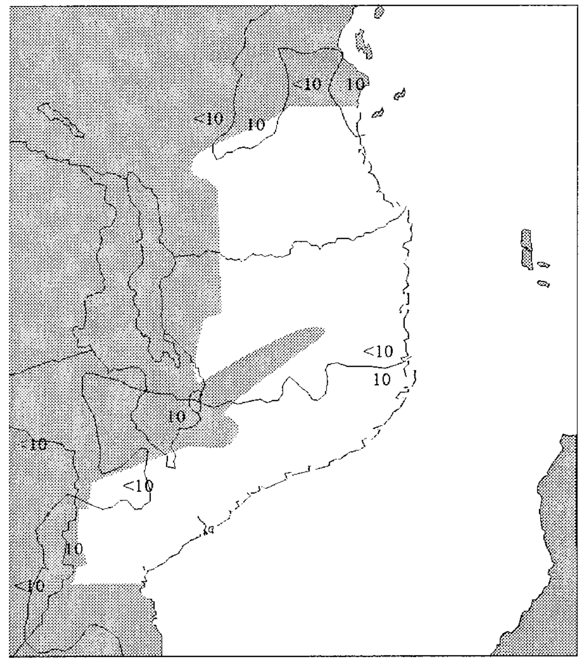


Figure 10-14. August Mean Precipitation (mm).

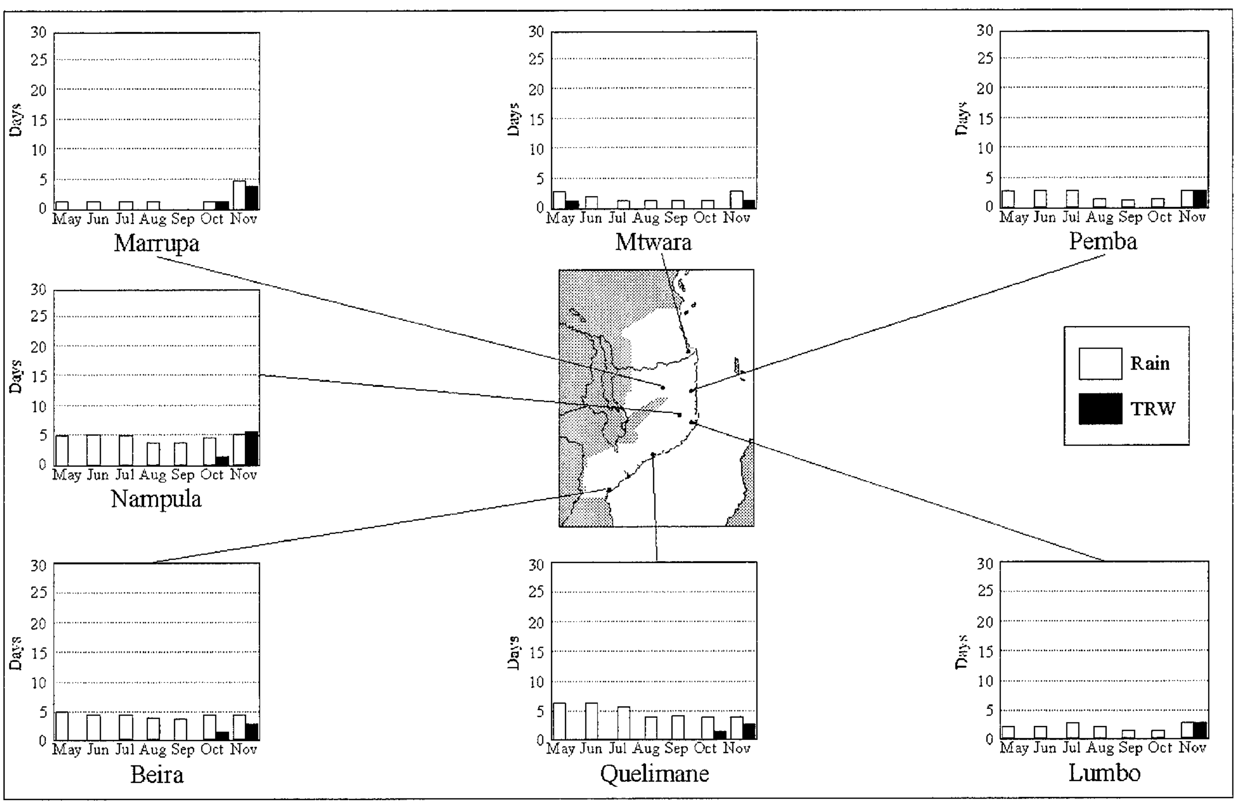


Figure 10-15. Dry-Season Mean Rain and Thunderstorm Days.

Temperatures. Winter dry-season temperatures are slightly lower than those of the wet season (see Figures 10-16 and 10-17). Average highs are generally 24 to 26° C. Average lows are near 17° C. At Quelimane, extreme temperatures in July are 33 and 9° C. In the highlands, Marrupa has extremes of 27 and 10° C.

Average wet-bulb globe temperatures vary from 26° C along the coast to 23° C in the interior.

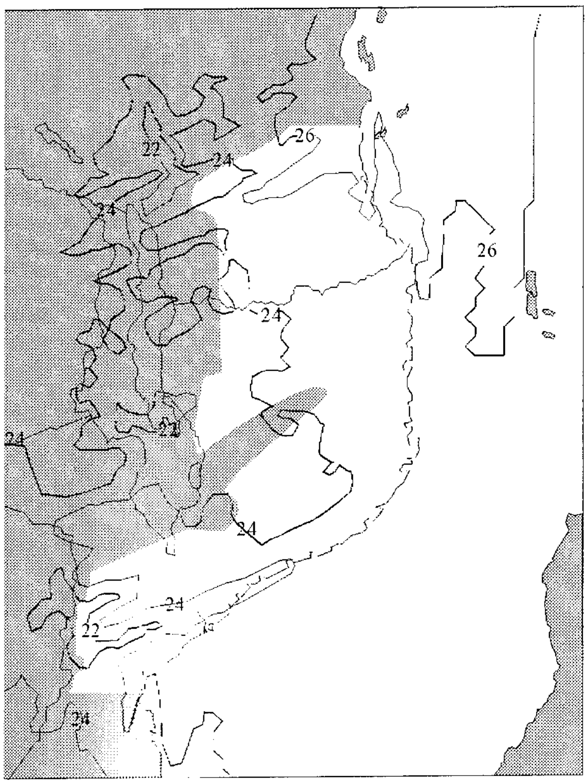


Figure 10-16. July Mean Maximum Temperatures (° C).

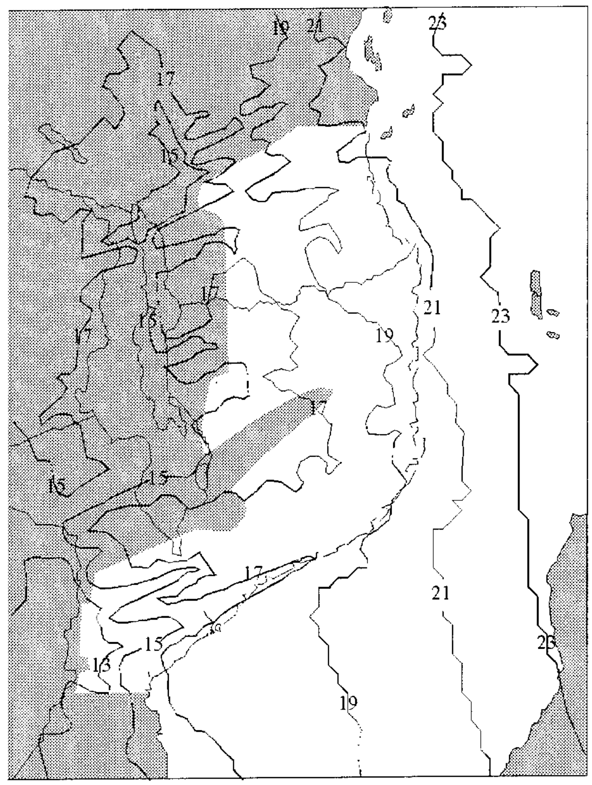


Figure 10-17. July Mean Minimum Temperatures (° C).

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319 OSS/OSW 695 STEEN AVE STE 106 GRAND FORKS AFB ND 58205-6244 1
347 OSS OSW 8227 KNIGHTS WAY STE 1062 MOODY AFB GA 31699-1899 1
355 OSS OSWF 4360 S PHOENIX ST BLDG 4820 DAVIS MONTHAN AFB AZ 85707-4638 1
366 OSS OSW 665 THUNDERBOLT ST BLDG 262 RM 11 MT HOME AFB ID 83648-5401 1
410 OSS OSW 401 F AVE STE 7 K I SAWYER AFB MI 49843-401 1
416 OSS OSW 592 HANGAR RD BLDG 1000 STE 121 GRIFFISS AFB NY 13441-4520 1
482 OG/OSAW 360 CORAL SEA BLVD HOMESTEAD AFS FL 33039-1299 1
509 OSS OSW 745 ARNOLD AVE STE 1A WHITEMAN AFB MO 65035-5026 1
DET 1 549 CTS/WX 661 7TH ST BICYCLE LAKE AAF BLDG 6212 FORT IRWIN CA 92310-5000 1
608 COS/DOOW 245 DAVIS AVE EAST BLDG 5546 STE 245 BARKSDALE AFB LA 71110-2279 1
758 AS/DOV 316 DEFENSE AVE STE 101 CORAOPOLIS PA 15108-4403 1
901 AG/OSA USAFR (KEN GOULD) 3976 KING GRAVES RD YOUNGSTOWN/WARREN MAP VIENNA OH 44473-0910 1

AETC/XOSW 1F ST STE 2 RANDOLPH AFB TX 78150-4325 1
AFIT LDEE 2950 P ST BLDG 640 WRIGHT-PATTERSON AFB OH 45433-7765 1
AFIT CIR WRIGHT-PATTERSON AFB OH 45433-6583 1
AU/ACSC (MAJOR MUOLO/DEA) 225 CHENNAULT CIRCLE MAXWELL AFB AL 36112-6426 1
12 OSS DOW H 08, 1350 5TH ST EAST RANDOLPH AFB TX 78150-4410 1
14 OSS DOW 595 1ST ST STE # 3 COLUMBUS AFB MS 39710-4201 1
42 OS/OSWF 220 WEST ASH BLDG 844 MAXWELL AFB AL 36112-6608 1
45 AS/OSFWX 817 H ST STE 102 KEESLER AFB MS 39534-2452 1
47 OSS DOW 541 1ST ST STE 2 LAUGHLIN AFB TX 78843-5210 1
56 OSS/OSW 14185 WEST FALCON LUKE AFB AZ 85309-1629 1
OL A 58 OSS OSW BLDG 324 GILA BEND AFAF AZ 85337-5000 1
64 OSS DOW 145 N DAVIS DR REESE AFB TX 79489-5000 1
71 OSS/OSW 301 GRITZ ST STE 52 VANCE AFB OK 73705-5412 1
80 OSS/DOAW 620 J AVENUE STE 3 SHEPPARD AFB TX 76311-2553 1
97 OSS WXF 603 E AVE STE 1 ALTUS AFB OK 73523-5033 1
325 OSS OSW STOP 22 408 FLIGHTINE RD2 TYNDALL AFB FL 32403-5124 1
333 TCHTS TTCJB 600 FIRST STREET STE 101 KEESLER AFB MS 39534-2494 1
334 TRS TTMV 700 H ST BLDG 4332 KEESLER AFB MS 39534-2499 1
558 FTS 2065 1ST DRIVE WEST RANDOLPH AFB TX 78150-4351 1

NAIC TATW 4115 HEBBLE CREEK ROAD STE 33 WRIGHT-PATTERSON AFB OH 45433-5637 1
AFCESA WE STOP 21 TYNDALL AFB FL 32403-6001 1
AFMC DOW 4225 LOGISTICS AVE STE 2 WRIGHT-PATTERSON AFB OH 45433-5714 1
AFOTEC/WE 8500 GIBSON BLVD SE KIRTLAND AFB NM 87117-5558 1
AL/OEBE ARMSTRONG LABORATORY 2402 EAST DRIVE BROOKS AFB TX 78235-5114 1
ASC/WE BLDG 91 3RD ST WRIGHT-PATTERSON AFB OH 45433-6503 1
ESC ENS 5 EGLIN ST HANSCOM AFB MA 01731-2116 1
ESC WE 5 EGLIN ST HANSCOM AFB MA 01731-2172 1

PL/GP 29 RANDOLPH ROAD HANSCOM AFB MA 01731-3010 1
PL/TSML 5 WRIGHT ST HANSCOM AFB MA 01731-3004 1
PL/GPOA (AFDIS POC) 29 RANDOLPH RD HANSCOM AFB MA 01731-3010 1
PL/LIAF 3550 ABERDEEN AVE SE KIRTLAND AFB NM 87117-5776 1
PL/LIMI 3550 ABERDEEN AVE SE KIRTLAND AFB NM 87117-5776 1
PL WE 3350 ABERDEEN AVENUE KIRTLAND AFB NM 87117-5776 1
RL/WE 525 BROOKS RD GRIFFISS AFB NY 13441-4505 1
SMC SDEW 160 SKYNET ST STE 2315 LOS ANGELES CA 90245-4683 1
WL/DOWM 2130 8TH ST STE 11 WRIGHT PATTERSON AFB OH 45433-7552 1

46 OSS/OSWA 601 W CHOCTAWHATCHEE AVE STE 60 EGLIN AFB FL 32542-5719 1
46 TW/TSWG 211 W EGLIN BLVD STE 128 EGLIN AFB FL 32542-5429 1
46 TEST GROUP WE 871 DEZONIA DRIVE BLDG 1183 HOLLOMAN AFB NM 88330-7715 1
72 OSS OSW 3800 A AVE BLDG 240 TINKER AFB OK 73145-9108 1
75 OSS/OSWT 5970 SOUTHGATE DR HILL AFB UT 84056-5232 1
76 OSS OSW 303 LUKE DR, STE 1 KELLY AFB TX 78241-5638 1
77 OSS/OSW 3028 PEACEKEEPER STE 4 MCCLELLAN AFB CA 95652-1020 1
78 OSS/OSW 200 EAGLE ST STE 202 ROBINS AFB GA 31098-2602 1
88 OSS/OSWA 2049 MONAHAN WAY BLDG 91 WRIGHT-PATTERSON AFB OH 45433-7204 1
88 OSS/OSWB 5291 SKEEL AVENUE STE 1 WRIGHT-PATTERSON AFB OH 45433-5231 1
412 OSS/WE 85 S FLIGHTLINE RD BLDG 1200 EDWARDS AFB CA 93524-6460 1
647 SVS/SVBMA (JASON SMITH) 98 BARKSDALE ST HANSCOM AFB MA 01731-1807 1
AFSOC DOOWO 100 BARTLEY ST HURLBURT FLD FL 32544-5273 1
16 OSS/OGSW 150 BENNETT AVE BLDG 90730 HURLBURT FIELD FL 32544-5727 1
193 SOG DOW BLDG 19-101 RM 108 ASF 1 INDIANTOWN GAP ANNVILLE PA 17003-5005 1

USSPACECOM J3W 250 S PETERSON BLVD STE 116 PETERSON AFB CO 80914-3220 1
AFSPACECOM/DOGW 150 VANDENBERG ST STE 1105 PETERSON AFB CO 80914-4200 1
30 WS/DOV 900 CORAL RD BLDG 21150 VANDENBERG AFB CA 93437-5001 1
ADF WE STOP 77 18201 E DEVILS THUMB AVE AURORA CO 80011-9536 1
AFSFC SYT 715 KEPLER AVE STE 60 FALCON AFB CO 80918-7160 1
CAPE CANAVERAL FORECAST FACILITY/ROCC BLDG 81900 CAPE CANAVERAL AFS FL 32925-6537 1
DET 2 SMC/TDOR (WEATHER) 1080 LOCKHEED WAY BOX 044 ONIZUKA AFB CA 94088-1235 1
21 OSS OGSW 125 W HAMILTON AVE PETERSON AFB CO 80914-1220 1
30 WS 900 CORRAL RD BLDG 21150 VANDENBERG AFB CA 93437-5002 1
30 WS/DOV 900 CORAL RD BLDG 21150 VANDENBERG AFB CA 93437-5001 1
45 WS/DOO 1201 MINUTEMAN ST PATRICK AFB FL 32925-3238 1
50 OSS WE 300 O'MALLEY AVE STE 26 FALCON AFB CO 80912-3026 1
90 OSS DOW 7505 SABER RD BLDG 1250 RM 1AF F E WARREN AFB WY 82005-2684 1
341 OSS DOW 7224 FLIGHTLINE DR ROOM 209 MALMSTROM AFB MT 59402-7526 1
SWC/DOB (STOP 8202) 720 IRWIN AVE FALCON AFB CO 80912-7210 1

AMC/DOWR 402 SCOTT DR UNIT 3A1 SCOTT AFB IL 62225-5302 1
AMC/XOWX 402 SCOTT DR UNIT 3A1 SCOTT AFB IL 62225-5302 1
AMWC/WCOXI 5656 TEXAS AVENUE FT DIX NJ 08640-5000 1
TACC/WXF 402 SCOTT DRIVE RM 132 SCOTT AFB IL 62225-5029 1
15 AF DOW MARCH AFB CA 92518-5000 1
22 OSS OSW 53435 KANSAS CT STE 110 MCCONNELL AFB KS 67221-3720 1
60 OSS/OSW 401 SECOND STREET TRAVIS AFB CA 94535-5030 1
62 OSS/OSW 1172 E STREET RM 127 MCCHORD AFB WA 98438-1008 1
89 OSS/OSW 1240 MENOHER DR BLDG 1220 ANDREWS AFB MD 20331-6511 1
92 OSS/OSW 901 WEST BONG STE 101 FAIRCHILD AFB WA 99011-8529 1
305 OSS/OSW 1730 VANDENBERG AVENUE MCGUIRE AFB NJ 08641-5509 1
375 OSS/OSW 433 HANGAR RD SCOTT AFB IL 62225-5029 1
377 ABW OTW 3400 CLARK AVE SE KIRTLAND AFB NM 87117-5776 1
380 OSS/OSW 301 ARIZONA AVE STE 1AF PLATTSBURGH AFB NY 12903-2705 1
434 OSS/ATWX BLDG S 28 HOOSIER BLVD GRISSOM ARB IN 46971-5000 1
436 OSS/OSW 501 EAGLE WAY ST DOVER AFB DE 19902-7504 1
437 OSS/OSW 101 S BATES ST STE A BLDG 169 CHARLESTON AFB SC 29404-5013 1
722 OSS/OSW 2645 GRAEBER ST STE 3 MARCH AFB CA 92518-2331 1

US ATLANTIC COMMAND 1562 MITSCHER AVENUE STE 200 NORFOLK VA 23551-2488 1
USAFALCENT RA POPE AFB NC 28308-5000 1
USCENTCOM CCJ3-W BLDG 540 MACDILL AFB FL 33608-7001 1
USCINCPAC (J37) BOX 13 CAMP H.M. SMITH HI 96861-5025 1
USEUCOM J3 OD WE UNIT 30400 BOX 1000 APO AE 09128-4209 1
USSOCCENT SCJ2- SWO 7115 S BOUNDARY DRIVE MACDILL AFB FL 33621-5101 1
USSOCOM SOJ3 OW 7701 TAMPA POINT BLVD MACDILL AFB FL 33621-5323 1
USSOUTHCOM SWO UNIT 0640 APO AA 34001-5000 1
USSTRATCOM J 315 901 SAC BLVD STE 1B29 OFFUTT AFB NE 68113-6300 1
USSTRATCOM/J3615 901 SAC BLVD STE 1F14 OFFUTT AFB NE 68113-6700 1
USTRANSCOM J3/4 OW 508 SCOTT DR BLDG 1900 SCOTT AFB IL 62225-5357 1
USTRANSCOM J5-SC (MITRE AFDIS) 508 SCOTT DR BLDG 1900 SCOTT AFB IL 62225-5357 1
6 SOPS/DOD (CAPT BRANSON) 106 PEACEKEEPER DR STE 2N3 OFFUTT AFB NE 68113-4027 1
OL A SOCOS/WX BLDG AT 3275 BAY 50 FT BRAGG NC 28307-5203 1

NCDC LIBRARY FEDERAL BUILDING ASHEVILLE NC 28801-2733 1
NGDC/NOAA (ATTN: AF LIAISON OFFICER) MAIL CODE E/GC2 325 BROADWAY BOULDER CO 80333-3328 1
NIST PUBS PRODUCTION RM A635 ADMIN BLDG GAITHERSBURG MD 20899 1
NOAA LIBRARY-EOC4W5C4 ATTN: ACQ 6009 EXECUTIVE BLVD ROCKVILLE MD 20852 1
NOAA/NWS W/OM21 SSMC-2 ROOM 13148 1325 EAST-WEST HIGHWAY SILVER SPRING MD 20910-3283 1
NOAA/MASC LIBRARY MC5 325 BROADWAY BOULDER CO 80303-3328 1
NOAA CENTRAL LIBRARY 1315 EAST-WEST HIGHWAY STE 2000 SILVER SPRING MD 20910 1
NOAA/NWS W/OSD SSMC- 2 ROOM 12220 1325 EAST-WEST HIGHWAY SILVER SPRING MD 20910-3283 1
NWS W/OM21 1325 EAST-WEST HWY RM 13208 SILVER SPRING MD 20910 1
NWS W/OSD BLDG SSM C-2 EAST-WEST HWY SILVER SPRING MD 20910 1

PACAF DOW 25 E ST STE I232 HICKAM AFB HI 96853-5426 1
8 OSS WX UNIT 2139 BLDG 2858 APO AP 96264-2139 1
15 OSS/OSW 800 HANGAR AVE HICKAM AFB HI 96853-5244 1
18 OSS/OSW UNIT 5177 BOX 40 APO AP 96368-5177 1
25 ASOS/DOW 1102 WRIGHT AVE WHEELER AAF HI 96854-5200 1
35 OSS/OSW UNIT 5011 APO AP 96319-5011 1
36 OSS/OSW UNIT 14035 BOX AF APO AP 96543-4035 1
DET 1 36 OSS/OSJ PSC 489 BOX 20 FPO AP 96536-0051 1
51 OSS/DOW UNIT 2051 APO AP 96278-2072 1
374 OSS DOW UNIT 5222 APO AP 96328-5222 1
OL A 374 OSS APO AP 96343-0085 1

607 WEATHER SQUADRON/DO UNIT 15173 BLDG 1506 APO AP 96205-0108 2
607 COS/DOW UNIT 2072 APO AP 96278-2072 1
OL A 607 WEATHER SQUADRON UNIT 15630 BLDG 1610 APO AP 96208-0195 1
OL B 607 WEATHER SQUADRON UNIT 15242 BLDG S 252 UNIT 15242 APO AP 96205-0015 1
OL C 607 WEATHER SQUADRON UNIT 15676 BLDG S 3101 RM 4 APO AP 96297-0626 1
DET 1 607 WEATHER SQUADRON UNIT 15674 APO AP 96258-0674 1
OL A DET 1 607 WEATHER SQUADRON UNIT 15675 APO AP 96257-0675 1
OL B DET 1 607 WEATHER SQUADRON UNIT 15118 APO AP 06224-0420 1
DET 2 607 WEATHER SQUADRON UNIT 15200 BLDG S 819 APO AP 96271-0136 1
OL A DET 2 607 WEATHER SQUADRON UNIT 15673 APO AP 96218-0673 1

3 OSS WE 7TH ST BLDG 32235 ELMENDORF AFB AK 99506-3097 1
611 OSS/OSW 6900 9TH ST STE 205 ELMENDORF AFB AK 99506-2250 1
OL A DET 1 611 OSS/WE BLDG 47 432 RM 116 FT RICHARDSON AIN AK 99505-2250 1
354 OSS IM 1215 FLIGHT LINE AVE STE 2 EIELSON AFB AK 997026-1520 1
3 ASOS/GEW BLDG 1558 FT WAINWRIGHT AIN AK 99703-5200 1
DET 1 3 ASOS/GEW BLDG 1558 FT WAINWRIGHT AK 99703-5200 1

ARMED FORCES MEDICAL INTELLIGENCE CTR INFO SVCS DIV BLDG 1607 FT DETRICK FREDERICK MD 21702-5004 1
ARMY TRAINING AND DOCTRINE COMMAND ATDO-IW (ATTN: SWO) FT MONROE VA 23651-5000 1
ARMY RESEARCH LABORATORY BATTLEFIELD ENVIRONMENT DIR AMSRL-BE WHITE SANDS MISSILE RANGE NM 88002-5501 1
USASOC ATTN: AOIN-ST FT BRAGG NC 28307-5200 1
U.S. ARMY COMBAT SYS TEST ACTIVITY METEOROLOGY BRANCH, BLDG 1134 ATTN: STECS-PO-OM ABERDEEN PROVING GRND MD 21005-5059 1
COMMANDER US ARMY PACIFIC (APIN-OPW) FT SHAFTER HI 96858-5100 1
COMMANDER, FORCES COMMAND AFIN-ICW FT MCPHERSON GA 30330-6000 1
DIRECTOR USA-CETEC ATTN: GL-AE FT BELVOIR VA 22060-5546 1
DIRECTOR, USA REDSTONE TECHNICAL TEST CENTER ATTN: STERT-TE-F-MT REDSTONE ARSENAL AL 35898-8052 1
FIRST US ARMY ATTN STAFF WEATHER OFFICER FT MEADE MD 20755-7300 1
SECOND US ARMY AFKD-OPI-W (AFDIS POC) FT GILLEM GA 30050-5000 1
HQ DA DCS OPERATIONS AND PLANS ATTN: DAMO-ZD RM 3A538, 400 ARMY PENTAGON WASHINGTON DC 20330-5000 1
HQ 629TH MI BN (CEWI), 29TH ID (LIGHT) 7100 GREENBELT ROAD GREENBELT MD 20770-3398 1
FIFTH U.S. ARMY AFKB-OP (SWO) FT SAM HOUSTON TX 78234-7001 1
SIXTH US ARMY AFKC-OP-IS-SWO (AFDIS POC) PRESIDIO SAN FRANCISCO CA 94129-5000 1
HQ ARCENT AFRD-DSO-SWO FT MCPHERSON GA 30330-7000 1
LOS ALAMITOS AAF (MR ADAMS) BLDG 1 AFRC 11200 LEXINGTON DR LOS ALAMITOS CA 90720-5001 1
NATIONAL RANGE DIRECTORATE MET BRANCH ATTN: STEWS-NR-DA-F WHITE SANDS MISSILE RANGE NM 88002-5504 1

TECHNICAL LIBRARY DUGWAY PROVING GROUND DUGWAY UT 84022-5000 1
TEXCOM FSTD ATTN: CSTE-TFS-SP FT SILL OK 73503-6100 1
USA TECOM ATTN: AMSEL-TC-AM(BE) C O NVESD FT BELVOIR VA 22060-5677 1
USA INTELLIGENCE CTR (WEATHER SUPPORT TEAM) ATTN ATZS CDI-W FT HUACHUCA AI AZ 85613-6000 1
USA DUGWAY PROVING GROUND TROPICAL TEST SITE UNIT 7140 ATTN: STEDP-MT-TM-TP APO AA 34004-5000 1
USA TECOM ATTN: AMSEL-RD-NV-VMD (MET) FT BELVOIR VA 22060-5677 1
USA ARMY ENGINEER TOPOGRAPHIC LAB ATTN: CEETL-TD FT BELVOIR VA 22310-3864 1
USARSPACE (MOSC-OO) 1670 N NEWPORT RD STE 121 COLORADO SPRINGS CO 80916-2749 1
1CC AZSB-GTFD AH-64 CSM ATTACK FT CAMPBELL AI KY 42223-5000 1
160TH SOAR(A) ATTN: ADAV-ST-FS(MR LEVARN) 6950 38TH STREET FT CAMPBELL KY 42223-1291 1
OL A AFCOS FT RICHIE MD 21719-5010 1

AFESC/RDXT BLDG 1120 STOP 21 TYNDALL AFB FL 32403-5000 1
AFOSR/NL BOLLING AFB DC 20332-5000 1
AFRES/DOTSC 155 2ND ST ROBINS AFB GA 31098-1635 1
AFTAC/TMKS 1030 SOUTH HIGHWAY A1A PATRICK AFB FL 32925-3002 1
AFTAC/TNRE 1030 SOUTH HIGHWAY A1A PATRICK AFB FL 32925-3002 1
AFTAC/TNLW 1030 SOUTH HIGHWAY A1A PATRICK AFB FL 32925-3002 1
ANGRC/DOSW 3500 FETCHET AVENUE ANDREWS AFB MD 20331-5157 1
DET 3 DOWX 1900 WEST FLAMINGO STE 266 PO BOX 19070 LAS VEGAS NV 89119-5116 1

OFMC FEDERAL COORDINATOR FOR METEOROLOGY 8455 COLESVILLE ROAD STE 1500 SILVER SPRING MD 20910-5000 1
DEFENSE INTELLIGENCE AGENCY DIA D1W 1B DIAC RM A4-130 WASHINGTON DC 20340-6612 1
DTIC-FDAC CAMERON STATION ALEXANDRIA VA 22304-6145 1
US COAST GUARD RES & DEV CTR (AFDIS POC) 1082 SHENNCOSSETT RD GROTON CT 06340-6096 1
BUREAU OF METEOROLOGY TRAINING CENTER GPO BOX 1289K MELBOURNE AUSTRALIA 3001 1

USAFA DFEG FAIRCHILD HALL USAF ACADEMY CO 80840-5701 1
USAFA DEPT OF ECONOMICS & GEOGRAPHY COLORADO SPRINGS CO 80840-5701 1
USAFA DFP 2354 FAIRCHILD DR STE 2A6 USAF ACADEMY CO 80840-5701 1

HQ JTF-PP (LT STEADLRY/USN) APO AE 09784-5000 1
NATO IMS (OPS DIVISION) PSC 80 BOX 36 APO AE 09724-5000 1
NATO LMS/OPS STAFF METEOROLOGICAL OFFICER APO AE 09724 1
AFSOUTH (CMFWC CAPT STRAYER) PSC 813 BOX 136 FPO AE 09620-5000 1
HQ AFN (AF WEATHER) UNIT 25702 BOX 178 APO AE 09242-5000 1

USAFE/DOW UNIT 3050 BOX 15 BLDG 546 ROOM 306 APO AE 09094-5015 5
3 AF/DOW UNIT 4840 APO AE 09459-4840 1
5 ATAF WEA OFFICE (LTC CERASUOLO) 5 ATAF WEATHER CENTRE 36100 VINCENZA ITALY 1
10 OSS OSW UNIT 5605 BOX 175 APO AE 09470-5175 1

16 AF WE UNIT 6365 APO AE 09601-6365 1
17 AF/WE UNIT 4065 APO AE 09136-5000 1
31 OSS OSW UNIT 6170 BLDG 904 APO AE 09601-6170 1
39 OSS OSW UNIT 1075 BOX 275 APO AE 09824-0275 1
48 OSS DOM UNIT 5245 BOX 390 APO AE 09464-5390 1
52 OSS WEF UNIT 8870 BOX 270 APO AE 09126-0270 1
86 OSS DOWA/BASE WEATHER STATION UNIT 8495 APO AE 09094-8495 1
86 OSS/DOW UNIT 8495 APO AE 09094-8495 1
86 OSS/OSW UNIT 470 APO AE 09136-4070 1
86 OSS DOWB/WEATHER SUPPORT UNIT UNIT 8495 APO AE 09094-8495 1
100 OSS DOW UNIT 4965 BLDG 500 APO AE 09459-4965 1

617 WS UNIT 29351 BLDG 12 APO AE 09014-5000 4
A FLT 617 WS UNIT 29231 APO AE 09102-3737 1
DET 1 617 WS UNIT 30400 BOX 1000 APO AE 09128 1
DET 2 617 WS UNIT 20200 BLDG 1310 APO AE 09165-9816 1
DET 3 617 WS CMR 416 BOX S APO AE 09140-9998 1
DET 4 617 WS UNIT 7890 EUROPEAN FORECAST CENTER APO AE 09126-7890 1
DET 5 617 WS CMR 454 UNIT 31020 APO AE 09250-0047 1
DET 6 617 WS UNIT 29632 APO AE 09096-5000 1
DET 7 617 WS UNIT 28130 APO AE 09114-5000 1
DET 8 617 WS UNIT 25202 HQ V CORPS G2 SWO APO AE 09079-5000 1
DET 9 617 WS UNIT 28216 APO AE 09173-5000 1
DET 10 617 WS UNIT 26410 BLDG 543 RM 111 APO AE 09182-0006 1
OL A DET 8 617 WS UNIT 29719 BOX 363 APO AE 09028-3728 1
OL A 617 WS C/O 527 MI OPS APO AE 09157-5000 1
OL A DET 2 617 WS CMR 438 UNIT 5240 WEATHER OFFICE APO AE 09111-5000 1
OL B 617 WS CMR 423 APO AE 09107-5000 1
OL C 617 WS CMR 445 BOX 260 APO AE 09046-5000 2
OL D 617 WS C/O CMR 431 APO AE 09175-6321 1
OL E 617 WS UNIT 31401 BOX 6 APO AE 09630-0006 1

1610 ALSG(P) ATTN OIC WEATHER APO AE 09867-5000 1
4404 OSS/OSW ATTN AFDIS POC APO AE 09894-0408 1
4409 OG/WE (ATTN AFDIS POC) UNIT 66200 BOX 100 APO AE 09852-6200 1

COMNAVMETOCCOM CODE N312 STENNIS SPACE CTR MS 39529-5000 1
COMNAVMETOCCOM CODE N332 STENNIS SPACE CTR MS 39529-5001 1
COMNAVMETOCCOM/512 (LCDR FORD) 1020 BALCH BLVD STENNIS SPACE CENTER MS 39529-5005 1
COMNAVMETOCCOM (CODE N433) 1020 BALCH BLVD STENNIS SPACE CENTER MS 39529-5005 1
COMNAVSPECWARCOM (CODE N27 FORCE OCEANOGRAPHER) 2000 TRIDENT WAY SAN DIEGO CA 92155-5599 1
COMSECONDFLEET (CODE J335) FPO AE 09506-6000 1
COMSIXFLEET (CODE N312) CDR MCGEE FPO AE 09501-6002 1
FLENUMMETOCCEN ATTN: DAVE HUFF MONTEREY CA 93943-5005 1
FLENUMMETOCDET FEDERAL BUILDING ASHEVILLE NC 28801-2696 1
LIBRARIAN FLENUMMETOCEN MONTEREY CA 93943-5005 1
HQ USMC (CODE ASL-44/LT COL BROWN) 2 NAVY ANNEX WASHINGTON DC 20380-1775 1
MARINE WING SUPPORT GROUP 27 (WO) PSC BOX 8082 CHERRY POINT MCAS NC 28532-8082 2
NAVAL RESEARCH LABORATORY MONTEREY CA 93943-5006 1
NAVAL RESEARCH LABORATORY CODE 4180 WASHINGTON DC 20375 1
NAVAL RESEARCH LABORATORY CODE 4323 WASHINGTON DC 20375 1
NAVAL POSTGRADUATE SCHOOL CODE MR/HY (ROBERT HANEY) 589 DYER RD BLDG 235 RM 2AF
MONTEREY CA 93943-5114 1
NAVAL POSTGRADUATE SCHOOL CHMN DEPT OF METEOROLOGY CODE 63 MONTEREY CA 93943-5000 1
NAVAL AIR WARFARE CENTER-WEAPONS DIVISION GEOPHYSICAL SCIENCES BRANCH CODE 32AF
POINT MUGU CA 93042-5001 1
COMMANDING OFFICER NAVEURMETOCCEN PSC 819 BOX 31 FPO AE 09645-3200 1
OFFICER IN CHARCE NAVEURMETOCDET PSC 817 BOX 13 FPO AE 09622-0800 1
OFFICER IN CHARGE NAVEURMETOCDET PSC 814 BOX 22 FPO AE 09865 1
OFFICER IN CHARGE NAVEURMETOCDET PSC 812 BOX 3380 FPO AE 09627-3380 1
NAVICECEN (LT KLEIN) 4251 SUITLAND RD FOB#4 WASHINGTON DC 20395 1
COMMANDING OFFICER NAVICECEN 4301 SUITLAND ROAD FOB #4 WASHINGTON DC 20395-5108 1
NAVLANTMETOCDET PATUXENT RIVER NAS MD 20670-5103 1
NAVLANTMETOCDET (AFDIS POC) PSC 1001 BOX 35-W FPO AE 09508-0014 1
NAVLANTMETOCEN 931 3 RD AVE MCCADY BLDG NORFOLK NAS VA 23511-2394 1
NAVLANTMETOCEN CODE 50, ATTN: MET TEAM 931 3RD AVE MCCADY BLDG NORFOLK NAS VA 23511-2394 1
NAVOCEANO CODE N2513 1002 BALCH BLVD STENNIS SPACE CTR MS 39522-5001 1
NAVOCEANO CODE 9220 STENNIS SPACE CTR MS 39529-5001 1
NAVOCEANO CODE N25131 8100 RM 203D STENNIS SPACE CTR MS 39522-5001 2
MAURY OCEANOGRAPHIC LIBRARY NAVOCEANO N4312 BLDG 1003 STENNIS SPACE CTR MS 39522-5001 1
NAVPACMETOCCEN ATTN: TECH LIBRARY BOX 113 PEARL HARBOR HI 96860-7000 1

NAVPACMETOCCEN WEST GUAM/JTWC (AFDIS POC) PSC 489 BOX 2 FPO AP 96563-0051 1
NAVPACMETOCFAC NAS NORTH ISLAND SAN DIEGO CA 92135-5130 1
MOBILE ENVIRONMENTAL TEAM NAVPACMETOCFAC SAN DIEGO (AFDIS POC) PO BOX 357076 NAS NORTH ISLAND CA 92135-7076 1
NRAD (CODE 423/JIM BROYLES) 1045 MONTEREY VISTA WAY ENCINITAS CA 92024 2
OCEANOGRAPHER OF THE NAVY (AGCS KAEMPFER) US NAVAL OBSERVATORY BLDG 1 3450 MASS AVE WASHINGTON DC 20392-5421 1
STATION OPERATIONS AND MAINTENANCE SQDN ATTN METOC OFFICER (SGT DENATALE) MCAS YUMA AZ 85369-5020 1
US PACIFIC FLEET (N3WX) CSC/WILLIAM LITTLE 250 MAKALAPA DRIVE PEARL HARBOR HI 96860-7000 1
WEATHER SERVICE-MCAS PO BOX 55010 BEAUFORT SC 29904-5001 2
WEATHER SERVICE USMC (WO SMITH) MCAS BOX 555151 CAMP PENDLETON CA 92055-5151 2
WSO H & HS MARINE STATION WEA MCAS TUSTIN CA 92710-5000 1
1 MARINE EXPEDITIONARY FORCE COMMAND ELEMENT (RLO) CAMP PENDLETON CA 92055-5300 1

AEDC TECHNICAL LIBRARY FL2804 100 KINDEL DR STE C212 ARNOLD AFB TN 37389-3212 1
HUMAN RESOURCES TECHNICAL LIBRARY FL2870 AL/HR-DOKL 7909 LINDBERG DR RM 239 BLDG 578 BROOKS AFB TX 78235-5352 1
AFFTC TECHNICAL LIBRARY FL2806 412 TW/TSTL 307 E POPSON AVE BLDG 1400 RM 106 EDWARDS AFB CA 93524-6630 1
TECHNICAL LIBRARY FL2825 203 W EGLIN BLVD STE 300 EGLIN AFB FL 32542-6843 1
ROME LAB TECHNICAL LIBRARY FL2810 RL/SUL CORRIDOR W STE 262 26 ELECTRONIC PKWY BLDG 106 GRIFFISS AFB NY 13441-4514 1
ROME LAB RESEARCH LIBRARY FL2807 PL/TL (LIBRARY) 5 WRIGHT ST BLDG 1103 HANSCOM AFB MA 01731-3004 1
TECHNICAL LIBRARY FL2051 SA-ALC/CNL 485 QUENTIN ROOSEVELT RD BLDG 171 KELLY AFB TX 782416425 1
PHILIPS LAB TECHNICAL LIBRARY FL2809 PL/DOSUL 3400 ABERDEEN AVE SE BLDG 419 KIRTLAND AFB NM 87117-5776 1
AIR UNIVERSITY LIBRARY FL3386 AUL/LD 600 CHENNAULT CIRCLE BLDG 1405 MAXWELL AFB AL 36112-6424 1
AUL/LSE BLDG 1405 600 CHENNAULT CIRCLE MAXWELL AFB AL 36112-6424 1
TECHNICAL LIBRARY FL3100 HQ SSC/RMMI 201 E MOORE DR BLDG 856 RM 1701 MAXWELL AFB GUNTER ANNEX AL 36114-3005 1
TECHNICAL LIBRARY FL2513 45 SW CSR 5123 1030 S HWY A1A BLDG 989 RM A1-S3 BOX 4127 PATRICK AFB FL 32925-0127 1
TECHNICAL INFO CTR FL7050 AL/EQ-TIC 139 BARNES DR STE 2 BLDG 1120 TYNDALL AFB FL 32403-5323 1
TECHNICAL LIBRARY FL2827 30 SPW/XPOT 806 13TH ST STE A BLDG 7015 VANDENBERG AFB CA 93437-61111 1
WRIGHT LAB LIBRARY FL2802 WL/DOC 2690 C ST STE 4 BLDG 22 WRIGHT-PATTERSON AFB OH 45433-7411 1
TECHNICAL LIBRARY FL2830 NAIC/DXLS AREA A 415 HEBBLE CREEK RD STE 9 BLDG 856 WRIGHT-PATTERSON AFB OH 45433-6508 1
USAFA LIBRARY FL7000 HQ USAFA/DFSEL 2354 FAIRCHILD DR STE 3A10 USAF ACADEMY CO 80840-6214 1
AWS TECHNICAL LIBRARY FL4414 859 BUCHANAN ST SCOTT AFB IL 62225-5118 150